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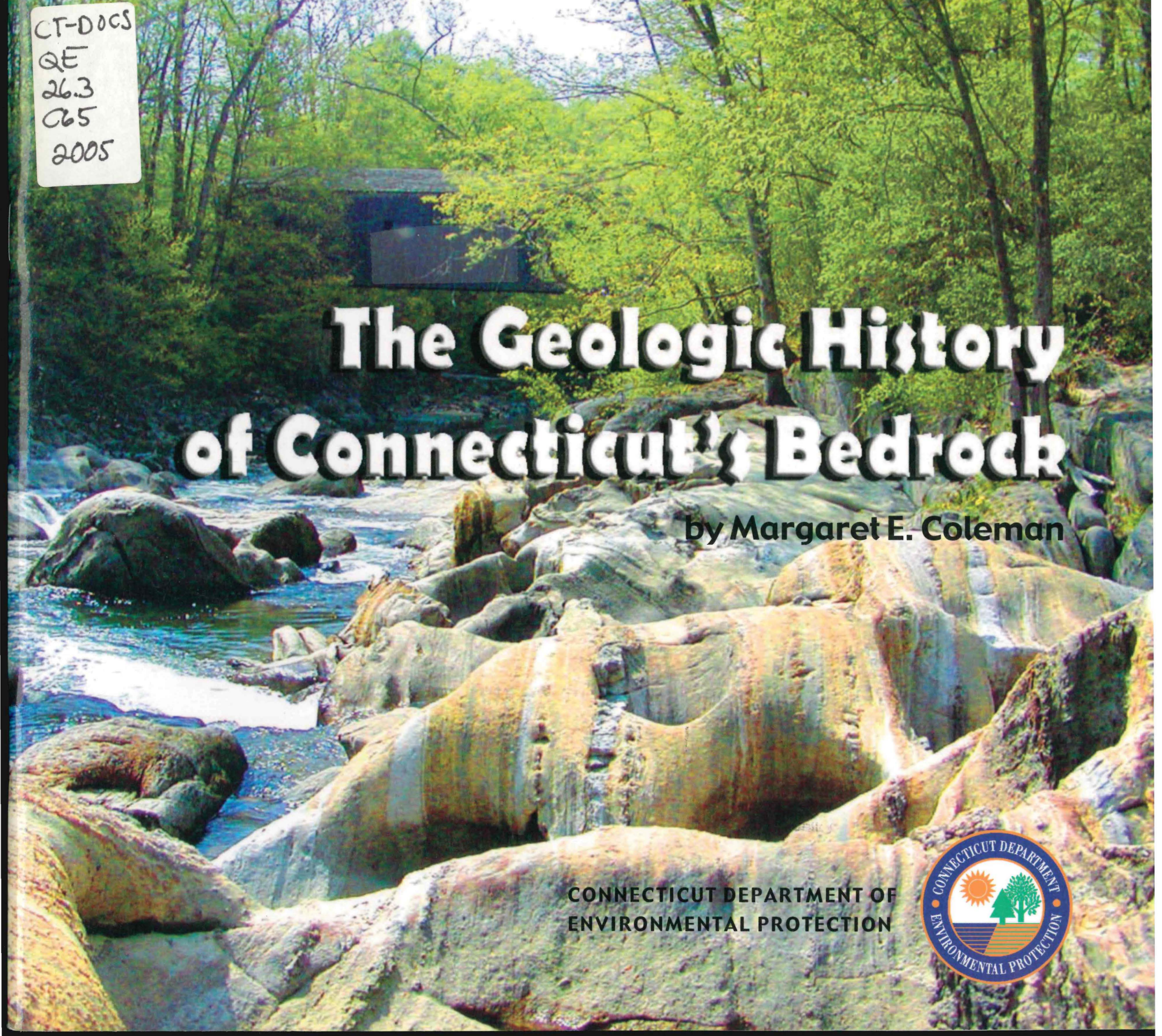

The Geologic History of Connecticut's Bedrock

by Margaret E. Coleman

CONNECTICUT DEPARTMENT OF
ENVIRONMENTAL PROTECTION

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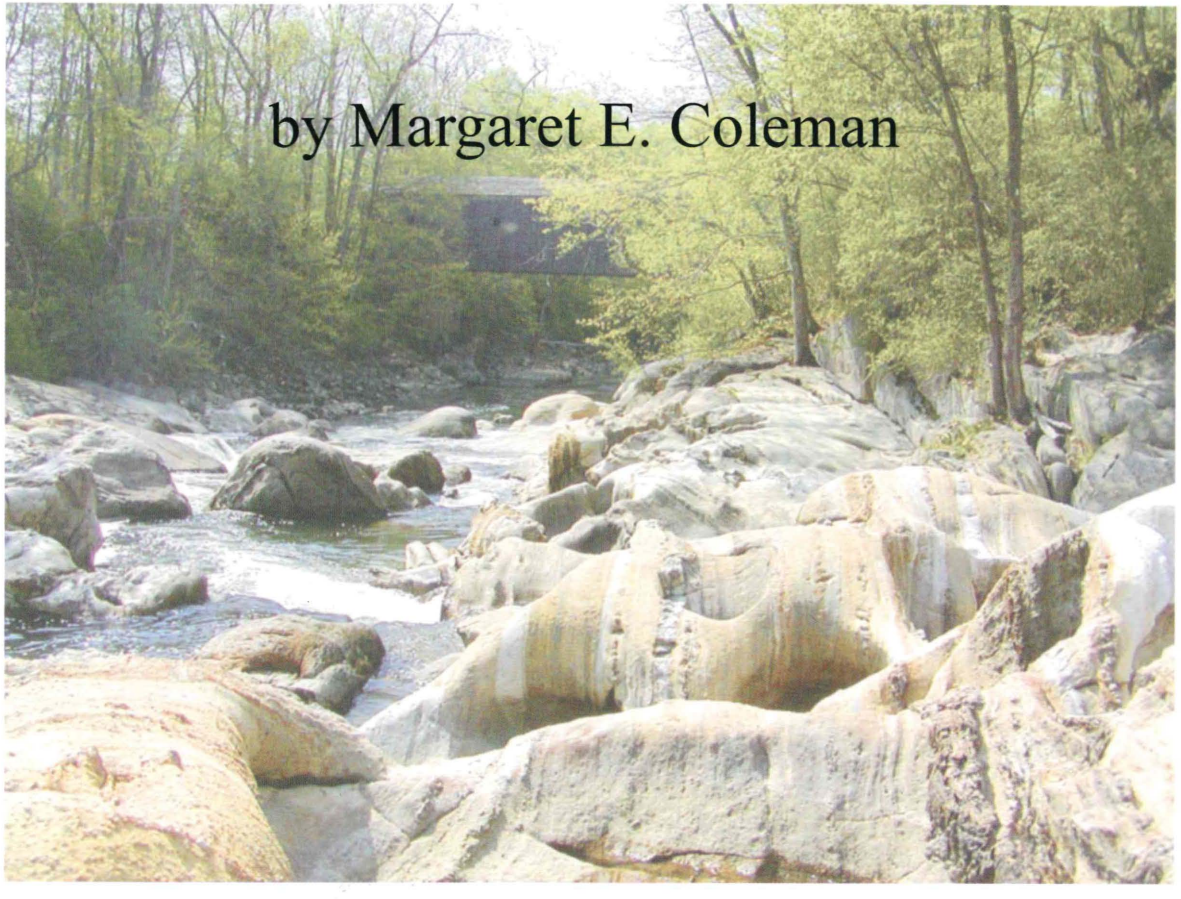

by Margaret E. Coleman

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Front cover photo: Potholes in marble, Housatonic River just north of Bulls Bridge, CT. Former coral reefs of the Cambro-Ordovician Shelf Sequence. Photo by Nancy W. McHone.

Back cover photo: Numerous continental collisions left former ocean floor sediments metamorphosed into banded gneiss in eastern and western Connecticut. Photo by Ralph S. Lewis.

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Acknowledgements

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Meg Coleman

ERA	PERIOD	Start of Period (Mya)
Cenozoic	Quaternary	2
	Tertiary	65
Mesozoic	Cretaceous	144
	Jurassic	206
	Triassic	248
Paleozoic	Permian	290
	Carboniferous	354
	Devonian	417
	Silurian	443
	Ordovician	490
	Cambrian	540
Precambrian	Neoproterozoic	1000
	Mesoproterozoic	4600

The geologic time scale (Scale is not proportional)

Introduction

The bedrock of Connecticut provides the foundation for its gentle rolling landscape, a landscape that seems old, permanent and unchanging. Although seemingly stable and constant, the rocks of Connecticut record more than a billion years of the Earth's dynamic and turbulent tectonic history. The rocks preserve pieces of evidence that point to a wide variety of vastly different environments that existed at different times, including a billion-year-old Himalayan-sized mountain **belt**, Ordovician (490- 443 million years ago (Mya)) tropical beaches, volcanic islands with active volcanoes, and Jurassic (206-144 Mya) rift valleys inhabited by dinosaurs. The clues to this varied and spectacular history lie within the igneous, metamorphic, and sedimentary rocks of Connecticut. Our understanding of the state's complex geology has gradually improved during two hundred years of geologic mapping and investigations.

This book chronicles Connecticut's bedrock geologic history within the context of regional **plate tectonic** events that assembled the modern day North American continent. Connecticut's bedrock was assembled in pieces from west to east during four major tectonic plate collisions. These collisions occurred over a 700 million-year period, and affected the entire eastern region of North America. The final plate collision was followed by the formation of the Atlantic Ocean, when Connecticut was nearly ripped in half. The assembly of many tectonic plates has created at least two giant continents called supercontinents in the history of the earth. The most recent supercontinent, Pangea, existed about 250 million years ago. Evidence for the existence and breakup of Pangea is clear in the shape of the modern continents that fit together like a jigsaw puzzle. An earlier supercontinent known as Rodinia formed about 1 billion years ago (Bya). But the events that occurred between the breakup of Rodinia and the formation of Pangea are less well understood because more recent tectonic events have scrambled the evidence. The history of the continents prior to Rodinia is pure speculation.

The oldest remnants of modern Connecticut formed when Rodinia split up and left behind the large continent of Laurentia. Younger rocks cover most of the original Laurentian rocks. But there are a few isolated regions along the Appalachians and in the southwestern United States where one can find these early Laurentian rocks at the surface. In Connecticut, exposures of these Precambrian (older than 540 Mya) Laurentian rocks can be found in the Berkshires of the western part of the state. Although they are the oldest rocks in the state, these rocks are difficult to distinguish upon inspection from the younger metamorphic rocks that surround them. Together these rocks have been metamorphosed and deformed during three major tectonic collisions. Separating the older Laurentian rocks from the younger rocks is like trying to distinguish the flour from the sugar layers in a cake mix after the ingredients were already blended and baked.

Connecticut as we know it today was left behind during the breakup of Pangea, when Africa split off from the supercontinent. In the 750 million intervening years between the formation of Rodinia and the break up of Pangea, three plate collisions and one rifting event greatly influenced the structure of Connecticut. These collisions created mountain chains comparable in magnificence and size to the volcanic islands of Japan and the majestic peaks of the Himalayas. But Connecticut also endured hundreds of millions of intervening years of **weathering** and at least two glaciations, so the once towering belts of sharp-peaked mountains have become the relatively modest and smooth Appalachians.

The following account of the tectonic events that assembled the bedrock of Connecticut is related to the Bedrock Geological Map of Connecticut compiled by John Rodgers (1985). The reader should be aware that this geologic account is a simplified synthesis taken from many different sources and therefore does not reflect all of the possible interpretations of Connecticut's geologic history. This account is an attempt to provide an up-to-date history within the limits of the current geological and geophysical data.

The author takes full responsibility for any oversimplification or biases, and the reader is encouraged to approach the geologic history of Connecticut with an open mind, as some of these interpretations will surely be modified in the future.

Remnants of a billion-year-old supercontinent

Most of the bedrock in Connecticut and much of North America, did not exist 500 million years ago. But some remnants of the billion-year-old supercontinent called Rodinia can be found in western Connecticut. These rocks provide rare glimpses into the geological foundation of Connecticut and all of North America.

The oldest rocks in the state—about 1.1 billion years old—are found in outcrops within the western highlands (Figure 1A). These rocks are part of a group in North America called the Grenville. They can be traced in a wide belt that extends from eastern Labrador as far south as Mexico. In Connecticut, the Grenville rocks are often referred to as the Precambrian **massifs** of the western highlands. Local formation names include the Fordham Gneiss and the Danbury Gneiss (Rodgers, 1985).

In the field, the billion-year-old rocks of the Precambrian massifs are not noticeably different from the younger rocks around them because a complex history has changed their original identity. They are metamorphic rocks that were previously sedimentary and igneous rocks before metamorphism. There are **gneisses** and **schists** that include sedimentary rocks which were once part of the Laurentian continental margin and offshore ocean floor. And there are granitic gneisses and **amphibolites** that originated as igneous rocks such as **granites**, **pegmatites**, and **diorites**. For both groups, metamorphism occurred during one or more tectonic plate collisions.

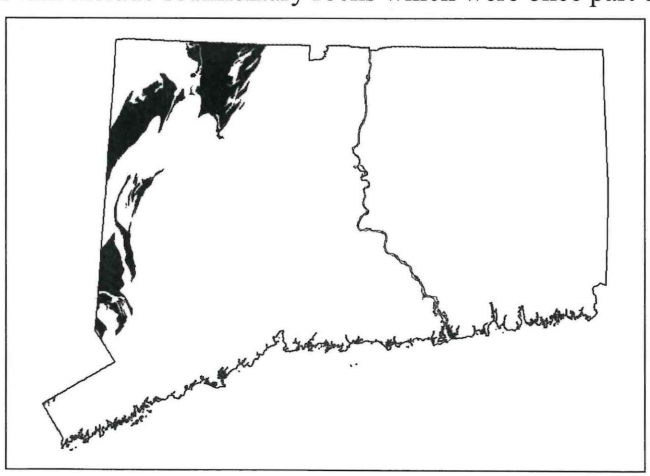


Figure 1A. Map of Connecticut with 1.1 billion year old rocks of western Connecticut in black.

The Grenville belt is buried in large part by younger rocks, and it is therefore commonly referred to as "basement" rock. We do not know much about the Grenville rocks in Connecticut, but we do know that a billion years ago they were deformed and metamorphosed by a major mountain building event called the "Grenville Orogeny". A large mountain chain was formed by continental masses colliding to form one huge landmass called Rodinia (Figure 1B). The Grenville rocks in Connecticut represent part of a large **suture** that joined the ancient North American Continent with other continents. Geologists have not been able to piece together the exact size and configuration of Rodinia, but evidence suggests that the east coast of North America was once against the west coast of South America (Amazonia) (Figure 1B & C). The history of the continental collision that formed the Himalayas is used as a model to help understand the processes that formed the billion-year-old Precambrian massif rocks that are now exposed in the western highlands of Connecticut (See "Link to the World" #1).

Over the next ~ 500 million years after the culmination of the Grenville Orogeny, the Grenville mountains sat quietly and gradually eroded away, exposing deeper and deeper levels of the **crust**. Sometime between 600 and 550 million years ago, the large continental landmass of Rodinia started to break apart and form a new ocean called the Iapetos Ocean. The separation of Rodinia left western Connecticut at the margin of the Iapetos Ocean. By about 540 million years ago western Connecticut was no longer in the middle of a large mountain range, but instead was reduced to sea level and sat at the edge of a growing ocean.

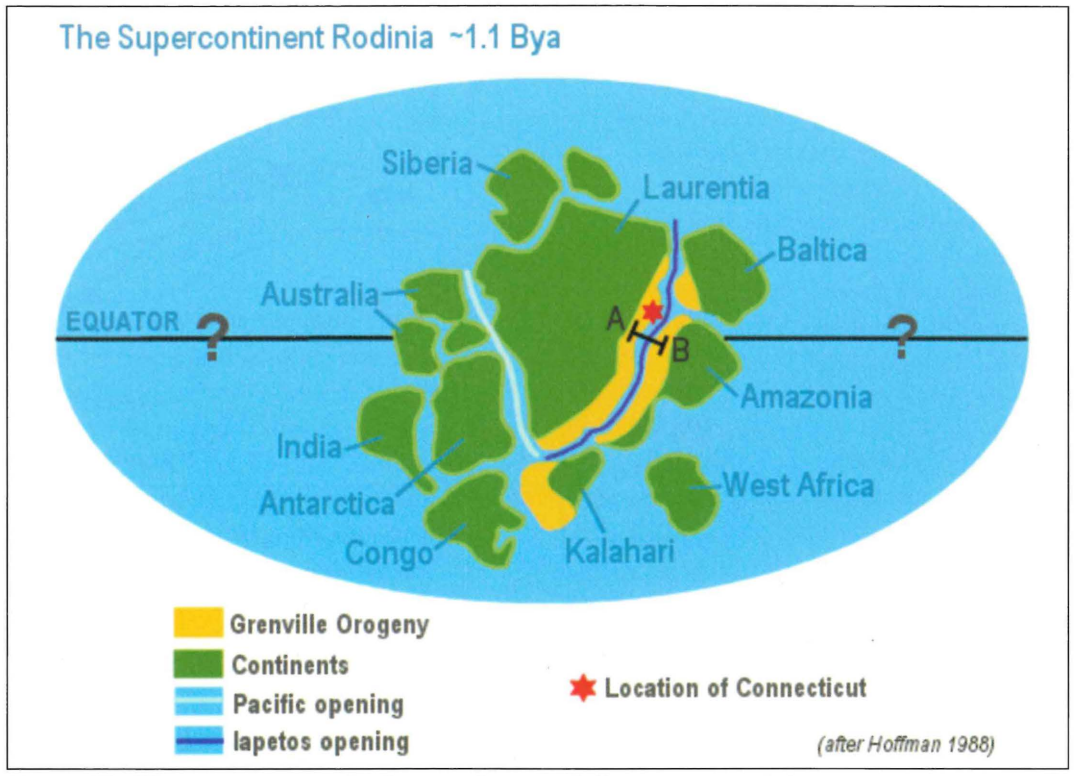


Figure 1B. The supercontinent Rodinia at about 1.1 billion years ago (after Hoffman, 1988).

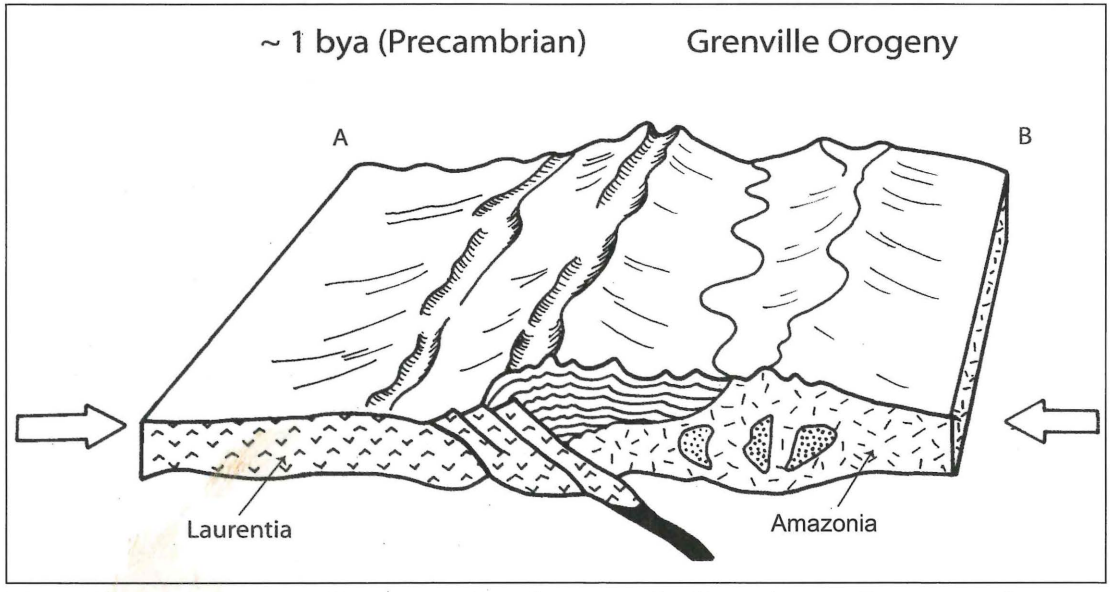


Figure 1C. Block diagram of the cross-section of continental collision between Laurentia and Amazonia roughly 1.1 billion years ago.

Link to the World #1

By studying active tectonic settings, geologists can find modern examples that help to explain what processes shaped ancient geologic terrains. To get a better idea of what was happening in western Connecticut a billion years ago, we can use the Himalayas for a modern day example. Why use the Himalayas to help us understand the oldest rocks in Connecticut? Because the Himalayas formed by the same process that formed the Grenville mountains, a continent-to-continent collision. Also the Himalayan collision is still happening and it has not been torn apart or overprinted by later tectonic events. In contrast, over the course of a billion years, the Grenville rocks of North America have been obscured by several different tectonic events that make it difficult to piece together the original anatomy of the ***orogeny****.*

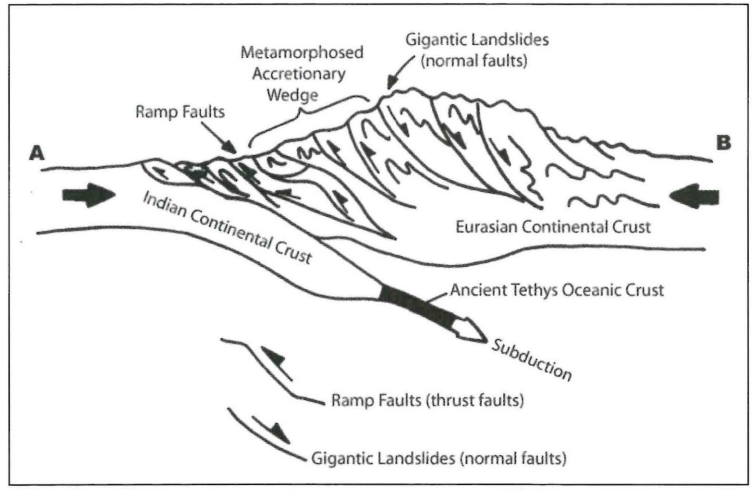


Figure 2B. Cross-section showing the profile of the Himalayan Mountains formed by the collision of the Eurasian and Indian Plates.

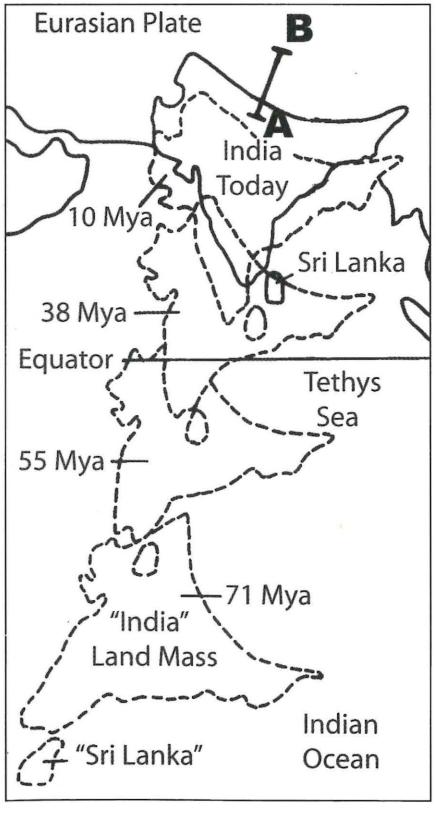


Figure 2A. The over 2,000 mile journey of the Indian Plate before its collision with the Eurasian Plate about 40 to 50 million years ago.

The Himalayas are continuing to be formed by the Indian sub-continent colliding with Eurasia (Figure 2A). The Tethys Sea, an ancient ocean between the two continents, completely disappeared by ***subduction*** *beneath Eurasia. The last Tethyan ocean crust subducted between 50 and 40 million years ago, but the Indian continent has continued to impinge on the Eurasian continent ever since. The spectacular Himalayas, reaching as high as 30,000 feet (Mt. Everest), are made of sedimentary rocks that were scraped off of the subducting Indian plate and Tethys sea floor. These rocks have been folded, faulted, buried, cooked, and squeezed by the ongoing head-on collision of the two plates. Many of the rocks exposed high within the Himalayas (5,000 - 15,000 ft above sea level) were buried as deep as 20 miles beneath the surface by about 20 million years ago and were completely transformed by metamorphism and partial melting. Deep levels of the crust within the mountain belt were brought back to the surface by a combination of forces. Continued compression from the collision caused ramp-like* ***faults*** *that brought deeper levels up on top of the earth's surface. Also, continual erosion at the earth's surface as well as large faults that behave similarly to gigantic landslides, helped to uncover these once deeply buried rocks (Figure 2B).*

Opening of the Iapetos Ocean

(570-490 Mya)

The break up of Rodinia started roughly six hundred million years ago (Figure 3). Fragments of Rodinia, including the ancient continents Laurentia (North America), Baltica (northern Europe), Siberia, and Amazonia, rifted away from each other, forming a new ocean called the Iapetos (Figure 4A, B & C) (see "Link to the World #2" for an explanation of continental rifting). The remaining pieces of Rodinia were joined into a large supercontinent, called Gondwana. After rifting progressed enough to form an ocean basin, western Connecticut became part of a continental margin and shallow continental shelf at the southern edge of Laurentia and remained that way for the next hundred million years.

Throughout the Early Cambrian (540-515 Mya), western Connecticut sat at the southern edge of the Laurentian continental margin at tropical southern latitudes. White sand beaches rimmed the coast at the base of subdued rocky hills, once the towering giants of the Grenville Orogen. At this time western Connecticut would have been at first glance a tropical paradise. However, despite beautiful beaches, there would not have been any palm trees to lie under, or any other vegetation for that matter. By the early Cambrian neither land plants nor animals had evolved yet. In the oceans, however, life was exploding and for the first time animals with hard shells flourished.

The stratigraphy of western Connecticut records the development of a tropical continental shelf on the southern coast of Laurentia (Figure 5A & B). A thick layer of white quartzite, called the Cheshire Quartzite, lies over the eroded Grenville basement (Figure 5A). Quartzite is the metamorphic product of **quartz** sandstone, which is in turn the **lithified** product of white sand. Stratigraphically above the Cheshire Quartzite lies more quartzite of the Dalton Formation, distinguished from the Cheshire by its greater **feldspar** content. During deposition of the beach sands the continental shelf gradually sank under the weight of the accumulating sand, and the beach deposits migrated further and further inland forming a broad continental shelf. By the end of the Cambrian period, sea level gradually rose and the entire continental shelf and most of Laurentia became drowned in a shallow sea. With no more land above sea level to erode and turn to sand, tropical shallow sea **carbonate** muds were laid down over the quartz sands (Figure 5A). The marbles of western Connecticut, called the Stockbridge Marbles, are the metamorphosed remains of the Late Cambrian carbonate platform. During the Late Cambrian and Early Ordovician western Connecticut would have been part of an expansive shallow sea. There would have been perhaps a few barren barrier islands with small beaches but very little land to stand on in Connecticut. Thick deposits of carbonate all over the eastern half of North America reveal that carbonate **deposition** continued throughout the Ordovician. The present distribution of these rocks is shown in Figure 5B.

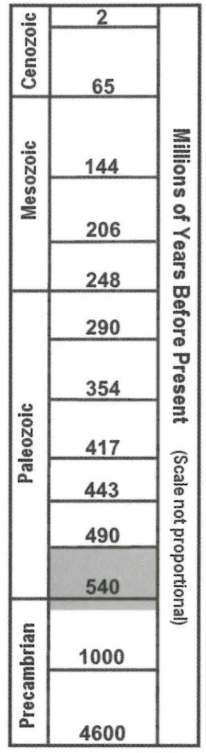


Figure 3. Geologic time scale with time frame highlighted for break up of Rodinia.

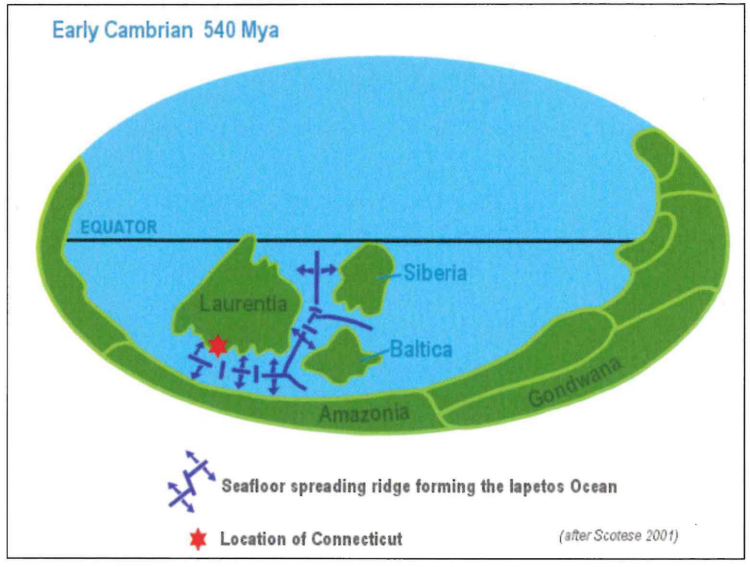


Figure 4A. Reconstruction of the position of the continents 540 million years ago (Modified from Scotese, 2001).

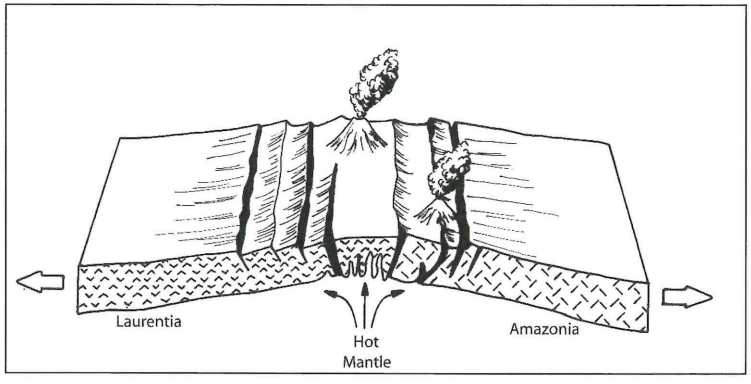


Figure 4B. Block diagram of initial stages of continental rifting that lead to the separation of Amazonia and Laurentia during the Late Proterozoic.

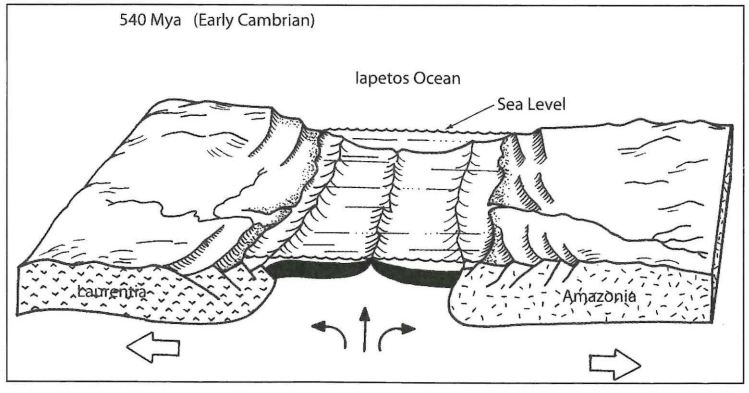


Figure 4C. Block diagram of formation of early Iapetos Ocean Basin formed by rifting of Laurentia and Amazonia during the early Cambrian.

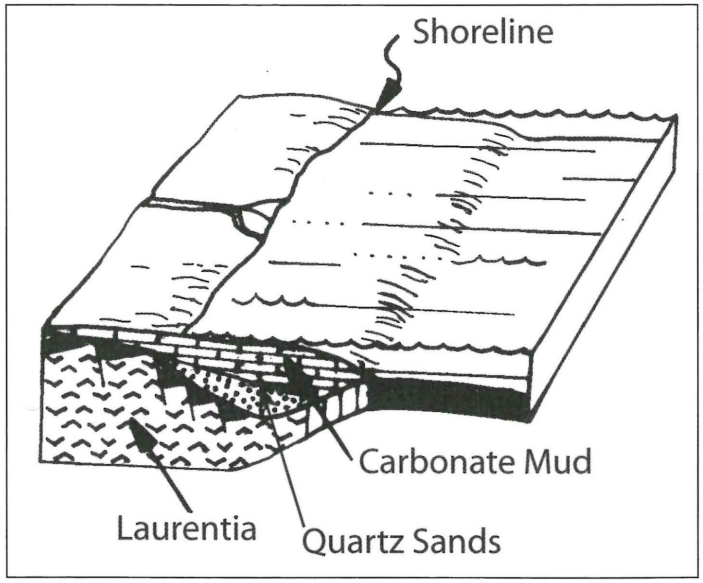


Figure 5A. Three-dimensional diagram of the hypothetical 520-470 million year old continental shelf that once occupied western Connecticut.

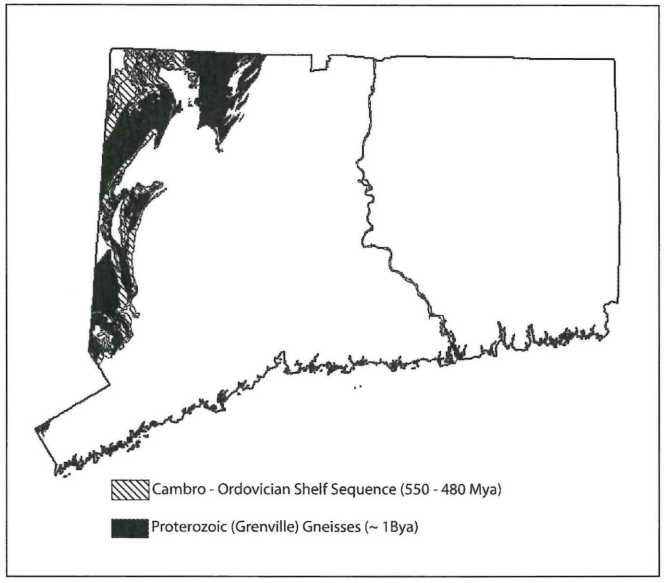


Figure 5B. Map of Connecticut showing the present day distribution of 550-480 million year old continental shelf sedimentary rocks (diagonal pattern), deposited on top of ~ billion year old metamorphic rocks (in black).

Link to the World #2

*It is thought that the cause of continental rifting is upwelling of hot **mantle** material that gradually erodes the overlying crust from below and pulls it apart (Figure 4B & C). When rifting progresses to the point when the continental crust breaks apart, mantle material reaches the earth's surface in the form of **basaltic** volcanism. If rifting continues, basaltic ocean crust is produced and a narrow ocean basin will form. Volcanic rocks that would accompany the rifting of Rodinia are missing in Connecticut but have been found further north in New England. Slivers of rocks called **greenstones**, in northern Vermont and southern Quebec, bear the chemical signature of rift volcanoes. These ancient volcanoes erupted about 550 million years ago, as Baltica started to pull away from Laurentia, after Amazonia, further to the south, had already rifted away. Modern day examples of rift volcanoes include the mighty volcanoes of the East African Rift Valley, Mt. Kenya and Mt. Kilimanjaro. The East African Rift is a continental rift in its early stages. The Red Sea is a continental rift that has progressed enough to form a narrow ocean basin (Figure 6).*

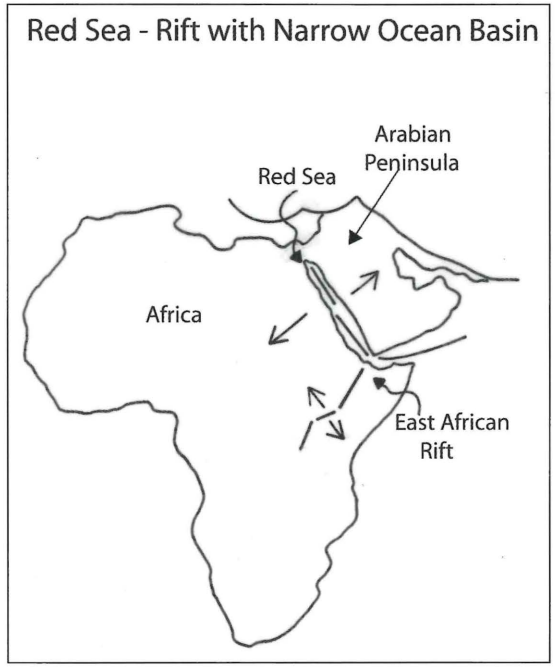


Figure 6. Map of the present day African and Arabian continents showing the location of continental rifting (arrows perpendicular to rifting).

The Iapetos Ocean begins to close (490-470 Mya)

Western Connecticut, during the Early Ordovician (490-470 Mya), remained part of the drowned Laurentian continental shelf, gradually accumulating carbonate mud (Figure 7). However, to the south and east of Laurentia, many miles away, the Iapetos Ocean basin started to close (Figure 8A). The northwestern half of the Iapetos Ocean floor gradually sank beneath a chain of volcanic islands, until the ocean basin closed and the volcanic islands collided with the southern margin of Laurentia (Figure 8B), dramatically changing the quiet shallow waters of the Ordovician carbonate shelf.

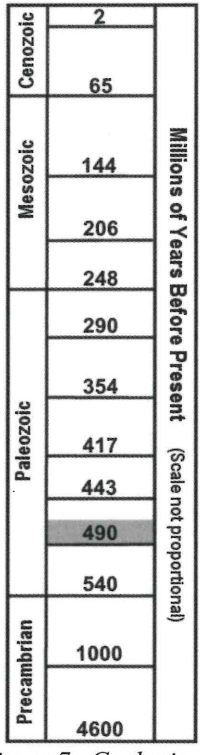


Figure 7. Geologic time scale with frame highlighted for Iapetos Ocean beginning to close.

The **subduction zone** that formed in the southern Iapetos during the Early Ordovician produced a long chain of volcanic islands called the Taconic Island Arc (Figure 8A & C) (see *Link to the World #3*). At the same time that the Taconic Island Arc was growing and gradually closing in on southern and eastern Laurentia, another distant tectonic event was taking place that would eventually impact the geology of Connecticut and North America. By about 480 million years ago, a piece of Precambrian continental crust rifted away from Gondwana and sat above another long southeastern-dipping subduction zone (the Nashoba Volcanic Arc). This piece of Gondwana, called Avalonia (Figure 8A & B), 100 million years in the future would be incorporated as part of North America during the Acadian Orogeny (400-350 million years ago).

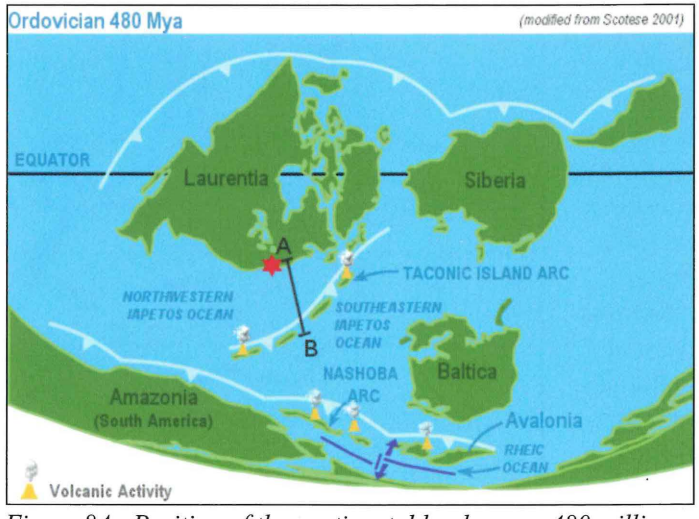


Figure 8A. Position of the continental landmasses 480 million years ago. The Taconic Island Arc forms by a subduction zone in the middle of the Iapetos Ocean. The Iapetos Ocean starts to close by subduction of oceanic crust beneath Amazonia and by subduction of oceanic crust beneath the Taconic Island Arc (Modified from Scotese, 2001).

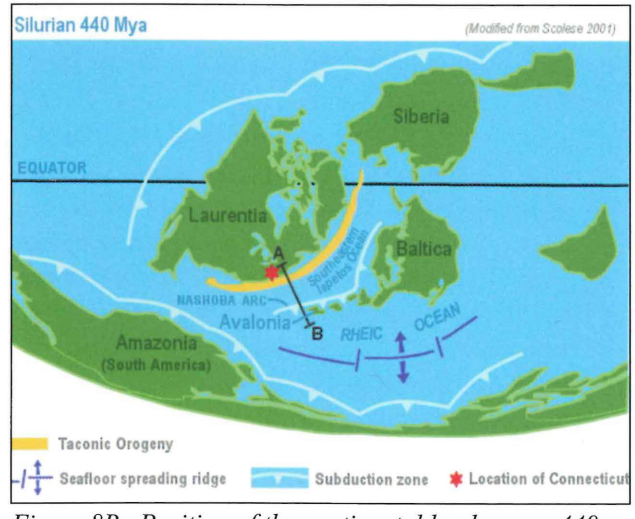


Figure 8B. Position of the continental landmasses 440 million years ago. The ocean basin between the Taconic Island Arc and Laurentia has closed and the Taconic Island Arc collides with Laurentia (North America) (Modified from Scotese, 2001).

Link to the World #3

Volcanic island arcs are chains of volcanic islands formed by the partial melting of sinking slabs of ocean crust. Modern day examples of volcanic island arcs include the Aleutian Islands of Alaska, Japan, and many of the islands that rim the western Pacific. The deep ocean ***trenches****, to the east of Japan and the Philippines, mark the top of a subducting oceanic plate. Island arcs are made up of both volcanic material derived from the melting subducting plate, and also thick wedges of ocean floor sediment, called* ***accretionary wedges****, that are scraped off of the sinking plate by the plate remaining above (Figure 9).*

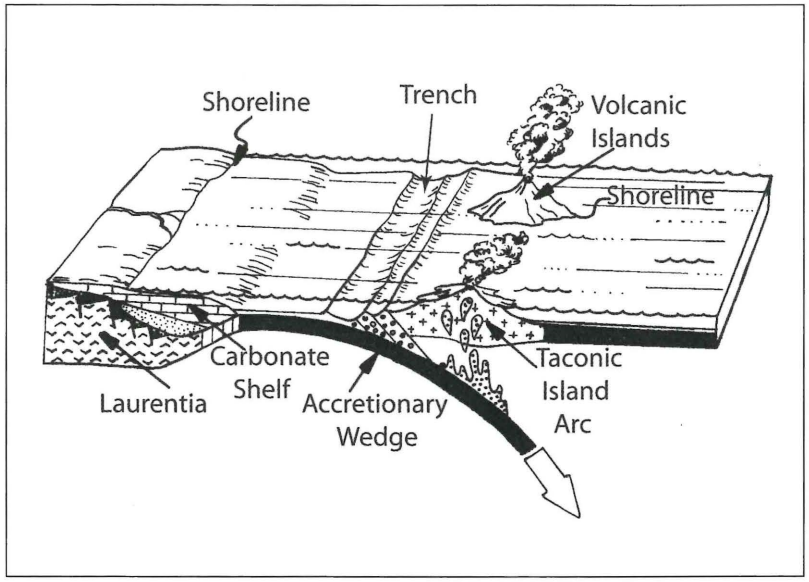


Figure 8C. Three-dimensional diagram of the Northwestern Iapetos Ocean from about 520-470 million years ago.

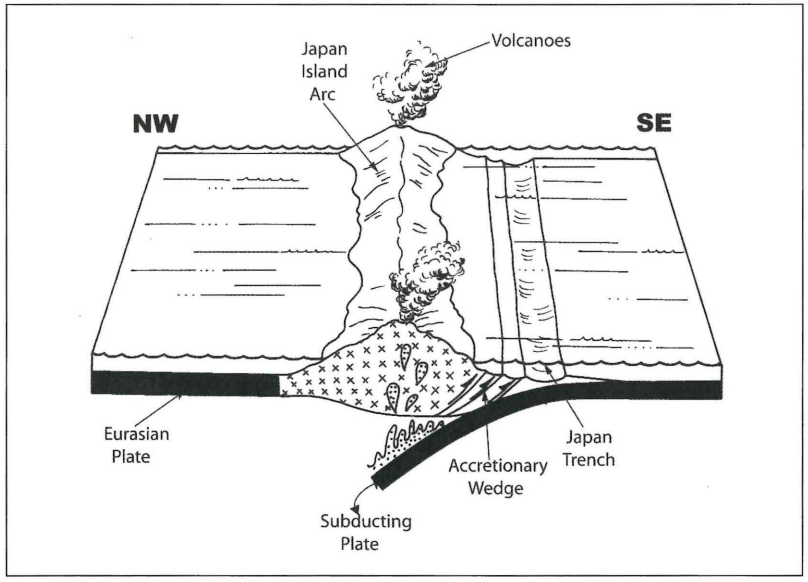


Figure 9. Three-dimensional block diagram of a subduction zone. The accretionary wedge is shown by the black arrows.

The first signs of an approaching island arc (470-460 Mya)

The Middle Ordovician sedimentary rocks of western Connecticut offer the first clues that the Taconic Arc was approaching the southern margin of Laurentia by 470 million years ago (Figure 10). These are indirect clues and require some explanation of the structure of the crust near a subduction zone. To the north of a south-dipping subduction zone, the tectonic plate being subducted is flexed into an arch by the bending of the plate. A flexed arch north of the Taconic Island Arc caused the drowned carbonate shelf of southern Laurentia (western Connecticut in today's reference frame) to rise above sea level and start to erode away (Figure 11A). After the continental shelf was lifted by the arch, it migrated toward the subduction zone. As this happened, the carbonate shelf reached the trench in front of the subduction zone and it became submerged several miles below sea level (Figure 11B). Deep-sea mud then started to accumulate on top of the carbonates.

In western Connecticut the dark Walloomsac Schist sits stratigraphically above the Stockbridge Marble (carbonate shelf rocks), and is the metamorphosed product of dark **shales**. The latter were originally muds deposited in the deepening waters as the Taconic Island Arc approached the Laurentian continental shelf. **Unconformities** in some areas of western Connecticut where dark schists sit directly above lower units of the Stockbridge marbles (with the middle units (younger) of the Stockbridge missing) provide evidence that the ancient carbonate shelf was uplifted and eroded.

In summary, the stratigraphy of the Cambro-Ordovician continental shelf records two key changes that signal the onset of the Taconic Orogeny; the uplift and erosion of the carbonate shelf, followed by rapid subsidence and deep-sea sediment deposition.

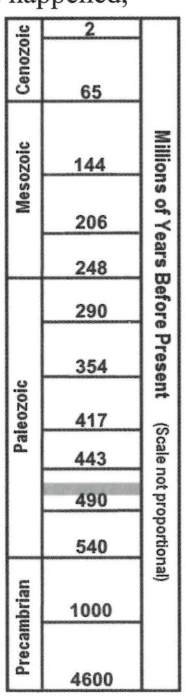


Figure 10. Geologic time scale with time frame highlighted for arrival of Tactonic Arc at the southern margin of Laurentia.

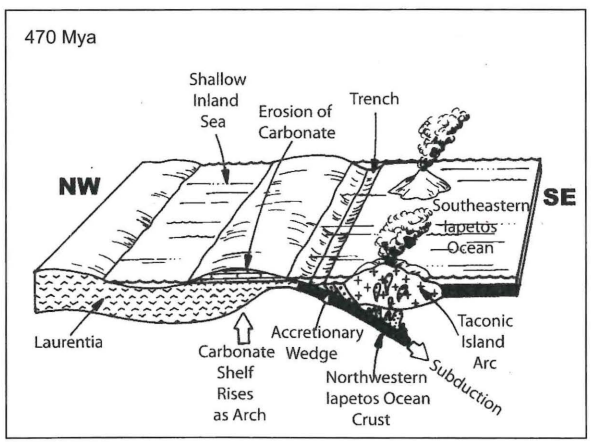


Figure 11A. A block diagram illustrating the position of the Taconic Island Arc relative to Laurentia (North America) 470 million years ago. The diagram shows the carbonate shelf bent into an arch from the flexing of the Laurentian Plate. The plate is flexed due to the subduction of the leading edge beneath the island arc. As a result the carbonate shelf is exposed above sea level and partially eroded.

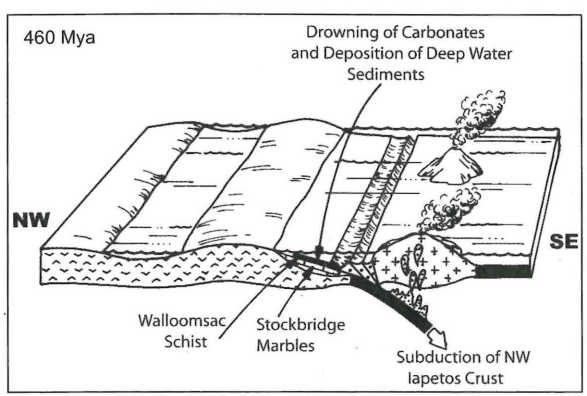


Figure 11B. Diagram illustrating the position of the Taconic Island Arc relative to Laurentia (North America) 460 million years ago. At this stage the carbonate shelf sediments have been dragged below sea level by the subducting plate and deep water sediments are deposited on top of the carbonate rocks, which are now metamorphosed to marble.

Closing of the northern Iapetus Ocean and the Taconic Orogeny (460-440 Mya)

During the Middle to Late Ordovician (~460-440 Mya, Figure 12), Connecticut and the entire southern margin of Laurentia merged with the Taconic Island Arc. The northern Iapetos Ocean gradually disappeared by subducting towards the southeast beneath the Taconic Island Arc (Figure 13A). The closure of the Iapetos Ocean and the joining of the Taconic Island Arc with Laurentia caused a major mountain building event called the Taconic **Orogeny**.

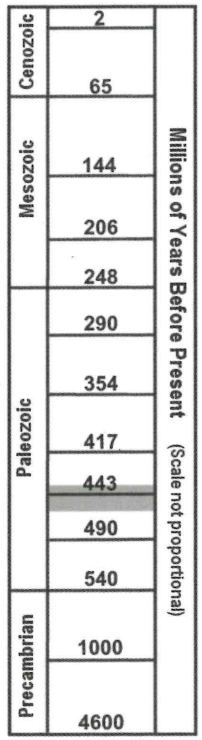


Figure 12. Geologic time scale with time frame highlighted for the Taconic Orogeny.

Taconic accretionary wedge and allochthons - slices of far traveled Iapetos Ocean floor

The Taconic mountain belt probably stood as high as the Alps. The mountains were made of folded and faulted rocks from the accretionary wedge of the Taconic Island Arc, rocks originally on the bottom of the Iapetos Ocean floor. By the time the island arc reached the southern margin of Laurentia, the accretionary wedge would have accumulated a very thick pile of faulted and folded deep-sea sedimentary rocks scraped off of the subducted northwestern Iapetos Ocean floor. Part of the accretionary wedge was plowed up along ramp-shaped faults by the Taconic Island Arc onto the younger carbonate shelf (Stockbridge Marbles), and onto the deep-sea sediments unconformably overlying the carbonate shelf (Walloomsac Schist), and the Precambrian basement of Laurentia. These rocks are referred to as the Taconic **allochthons**. Allochthons are rocks that have been displaced along fault surfaces a considerable distance from where they were originally deposited.

In Connecticut, the Taconic allochthons are slices of Late Cambrian (510-490 Mya) deep-sea sediments subsequently metamorphosed to schist. The formation names of Taconic allochthon rocks from Rodgers (1985) include the Hoosac, Manhattan, Everett, and Canaan Mountain schists (Figure 13B).

At the same time that the Taconic allochthons were shoved onto the continental shelf, the remaining part of the accretionary wedge was compressed between the continental margin of Laurentia and the Taconic Island Arc. In western Connecticut a large region of schists and gneisses, grouped together as the northwestern Iapetos **Terrane** (Figure 13B), are the metamorphosed remains of the Taconic accretionary wedge. In Connecticut this area includes the Hawley Formation, the Ratlum Mountain Schist, the Collinsville Formation, the Golden Hill Schist, and the Rowe Schist. The metamorphosed sedimentary rocks of western Connecticut are the only remains of the once vast northwestern Iapetos Ocean.

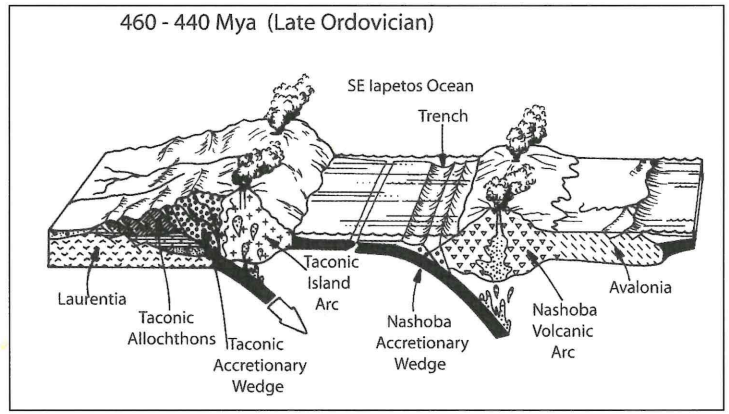


Figure 13A. Block diagram showing the addition of the Taconic Arc to Laurentia and subduction in the SE Iapetos Ocean beneath Avalonia (460-440 million years ago).

The Taconic volcanic arc

Once volcanoes become dormant they erode away within a few million years, quickly in geologic time. Therefore, little remains of the Ordovician (490-440 Mya) volcanoes of the Taconic Island Arc, but they were probably as spectacular as Japan's Mount Fuji. Metamorphosed remains of Ordovician volcanic rocks in Connecticut include the greenstones and schists of the Maltby Lake and Allingtown Formations within the Orange-Milford **belt**, and the **hornblende** gneiss and amphibolite of the Middletown Formation within the Bronson Hill **sequence**.

More extensive than the metamorphosed volcanic rocks of the Taconic Island Arc are the igneous rocks that once were part of large **magma** chambers that fed the overlying volcanoes. Magma chambers eventually cool and crystallize into coarse-grained igneous rocks (granites and diorites) beneath the surface of the earth. The remains of these magma chambers in Connecticut are large bodies of Ordovician granitic gneiss (metamorphosed granite). These granitic gneisses are part of a regionally extensive linear belt that extends from central Connecticut to Quebec and is referred to in New England geologic literature as the Bronson Hill sequence. In Connecticut the Taconic Island Arc granites include the Glastonbury Gneiss, the Monson Gneiss, granitic rocks within the Collinsville/Bristol **domes**, and a large unnamed granitic gneiss in western Connecticut (Figure 13B). The granitic rocks of the Glastonbury Gneiss are exposed within the Bolton Range of north central Connecticut.

Tectonics of the Southeastern Iapetos Ocean during the Taconic Orogeny

While the Taconic Island Arc was colliding with Laurentia, distant tectonic events were taking place in the southeastern Iapetos Ocean, which would eventually impact the geology of Connecticut. The rifted fragment of Gondwana, Avalonia, was moving north away from Gondwana and towards Laurentia. Moreover, a volcanic arc, the Nashoba Volcanic Arc, was forming on the northern edge of Avalonia above a south-dipping subduction zone (Figures 8B & 13A). The southeastern Iapetos Ocean was gradually shrinking as its crust subducted beneath Avalonia toward the south, and beneath Baltica toward the east (Figure 8B). Eventually, during the Devonian (~420-350 Mya) Acadian Orogeny, Avalonia and its Ordovician volcanic arc (Nashoba) would also collide with Laurentia and become part of Connecticut's bedrock.

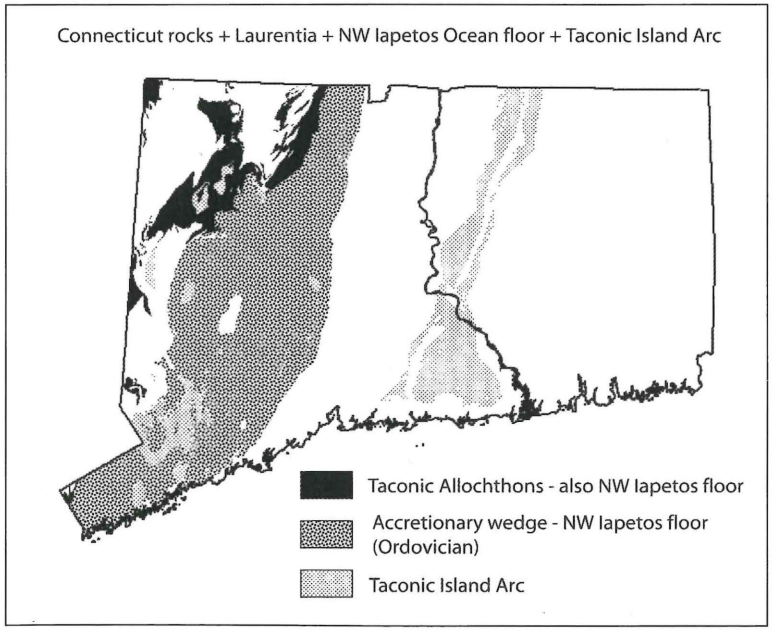


Figure 13B. Map of Connecticut that shows the present-day distribution of Taconic Allochthons, Taconic Island Arc, and Accretionary wedge. More occur in the center of the state, where they are covered by younger Mesozoic rocks.

Orogenic calm on the southern and eastern margin of Laurentia (440-400 Mya)

At the end of the Taconic Orogeny roughly half of Connecticut was assembled, and the topography of Connecticut probably resembled the mountainous volcanic islands of Japan or Taiwan. By the early Silurian (~440 Mya), the once mountainous terrain of Connecticut had almost completely eroded away and central Connecticut was part of a low lying coastal plain and shallow marine continental shelf. The majestic mountains produced by the Taconic Orogeny were diminished to gentle rolling hills in roughly 20 million years, a short time span in geologic terms. Once again Connecticut had white sand beaches rimming its coastline. There were still no palm trees, but land plants were beginning to colonize the barren landscape by the middle Silurian (~425 Mya). Over the next 40 million years (Figure 15B) Connecticut was no longer situated at an active plate boundary, but instead was part of a passive continental margin.

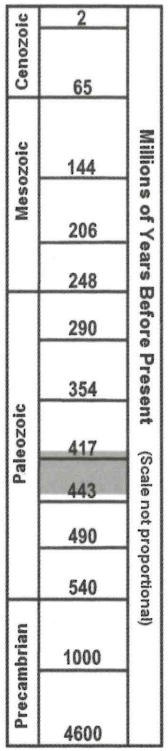


Figure 14. Geologic time scale with time frame highlighted for when central Connecticut was part of a passive continental margin.

In central Connecticut, there is a stratigraphic sequence of three metamorphosed sedimentary units, the Clough, Fitch, and Littleton formations (Figure 15A) that preserves a record of the Laurentian continental margin over a 40 million year period. These units are particularly well exposed in the steep hills of Bolton Notch in Bolton, Connecticut. Unfortunately, in Connecticut, these rocks retain very little of their original sedimentary features because they were metamorphosed and deformed beyond recognition during the following Acadian and Alleghenian orogenies. However, the same units can be traced all the way to northern New Hampshire where they escaped the same degree of metamorphism and contain fossils of former marine animals. The Clough and Fitch formations record deposition of beach and shallow continental shelf deposits during gradual subsidence of the shelf from about 440-420 million years ago. The Clough Formation, a white quartzite, lies unconformably above the eroded Taconic Island Arc (the Glastonbury Gneiss in Connecticut) (Figure 15B).

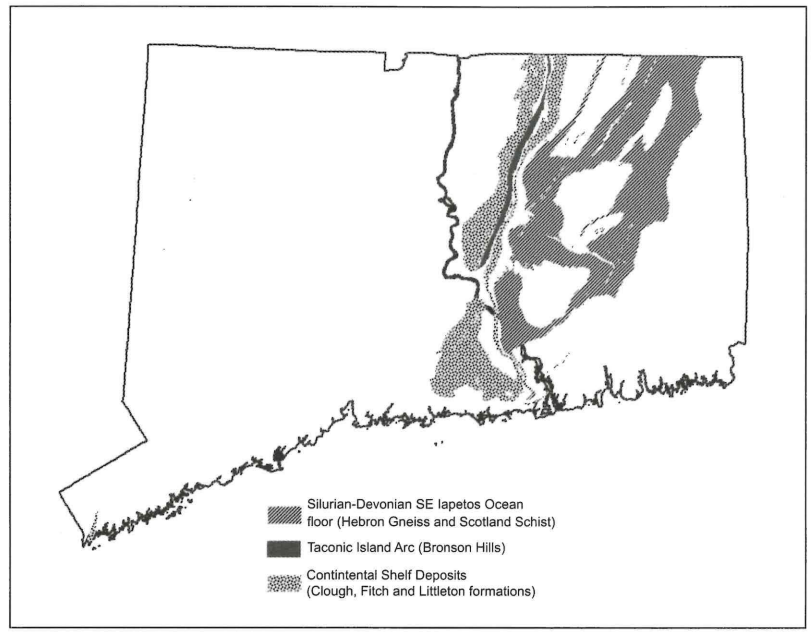


Figure 15A. Map of Connecticut that shows the present-day distribution of continental shelf rocks deposited on rocks of the Taconic Island Arc, and rocks originally on the ocean floor of the SE Iapetos Ocean.

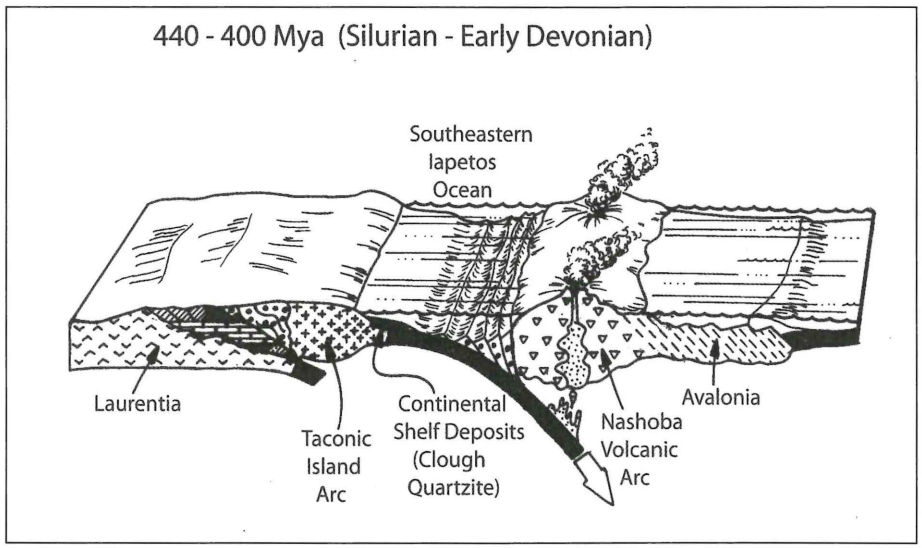


Figure 15B. Block diagram of North American margin (Laurentia), southeastern Iapetos Ocean, Nashoba Volcanic Arc and Avalonia (440-400 Mya).

Gradual subsidence of the continental shelf drowned the beaches (preserved in the Clough) so that carbonates were deposited on top of the sand, but with some silicate material derived from the eroded hills of the Taconic Mountains. The Fitch Formation is the metamorphosed remains of carbonaceous sandstones deposited on top of the Clough Quartzite. South of the Laurentian continental margin, deep-sea sediments were accumulating on the southeastern Iapetos Ocean floor. The remains of the southeastern Iapetos Ocean floor sediments include the Silurian (~440-420 Mya) and Devonian (~420-350 Mya) Hebron Gneiss and Scotland Schist in eastern Connecticut. The continental margin remained stable until the early Devonian (~420 Mya).

By the early Devonian most of the southeastern Iapetos Ocean floor had subducted toward the southeast beneath Avalonia. As the trench in front of Avalonia approached the continental shelf of Laurentia, the same process took place as when the Taconic Island Arc migrated towards Laurentia during the Ordovician. The trench gradually migrated over the Laurentian continental shelf, and caused the shelf to flex into an arch and erode. Erosion of the arch was followed by its drowning as it was dragged down into a deep-sea trench. Deep-sea muds that would become the Littleton Formation were deposited on top of the eroded carbonates of the Fitch Formation in a deep trough, hundreds of miles long. The remains of the deep-sea muds are the beautiful silvery schists of the Littleton Formation that were later metamorphosed to schists during the following orogenies. The rapid subsidence of the once passive continental margin signaled the approaching Nashoba Volcanic Arc and Avalonia "micro-continent", riding over the disappearing southeastern Iapetos Ocean. Connecticut, along with the entire eastern coast of Laurentia, was about to be pounded again, this time by Nashoba and Avalonia.

The Acadian Orogeny (440-350 Mya)

The Acadian Orogeny started with Baltica (western Europe, parts of Great Britain, and Scandinavia) colliding with northern Laurentia (Greenland) along an east dipping subduction zone in the Middle Silurian (440 Mya) (Figure 16). Greenland remained part of Laurentia throughout the Paleozoic. The collision of Baltica and Avalonia with Laurentia progressed from the northern shores of Laurentia towards the south, like a giant zipper closing from northeast to southwest. After Baltica hit Greenland it spun around in a clock-wise direction. Avalon, the southwestern arm of Baltica, collided with the Canadian Maritimes by the Late Silurian (~415 Mya) and then hit New England and the coast further southwest by the Devonian (400 Mya) (Figure 17A), finally coming to rest by the early Carboniferous (350 Mya).

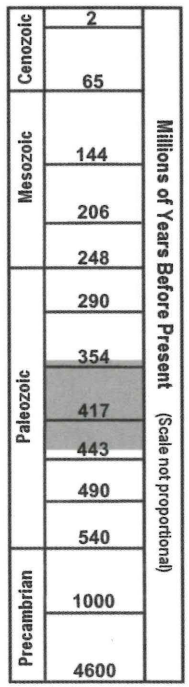


Figure 16. Geologic time scale with time frame highlighted for the Acadian Orogeny.

The Acadian Orogeny added most of the remaining bedrock that is now part of eastern North America. The merged Laurentia and Baltica is referred to in geologic literature as the "Old Red Sandstone Continent" because of an abundance of red sediments deposited in North America and northern Europe during the Late Devonian (370-354 Mya). Throughout much of the continent Old Red experienced a severe arid climate that produced oxidized red sediments. Despite the widespread arid climate, Old Red was a much more hospitable place than Laurentia. By the Middle Devonian (~390 Mya), plants were abundant, and lush swamps covered large areas of today's Canadian Arctic, Greenland and Scandinavia. In addition to land plants, fish with jaws evolved and dominated the seas by the end of the Devonian (~360 Mya).

The Acadian Orogeny progressed similarly to the Taconic Orogeny. As the last of the southeastern Iapetos Ocean crust disappeared down the subduction zone in front of Avalonia, the accretionary wedge that had formed above the subduction zone was pushed up against the Laurentian continental margin, to be followed by the Nashoba Volcanic Arc, and finally the Avalonian continental crust (Figure 17B).

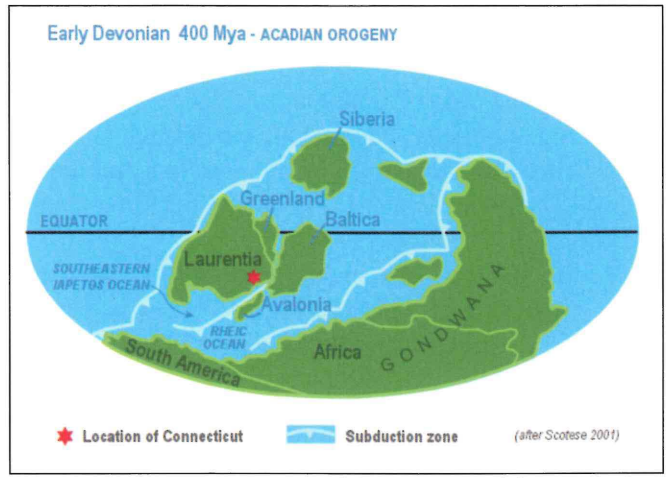


Figure 17A. Reconstruction of the position of the continents 400 Mya during the Acadian Orogeny (after Scotese 2001).

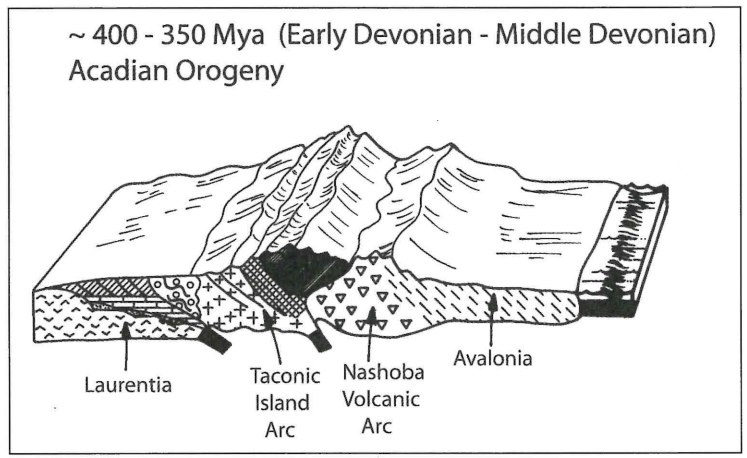


Figure 17B. Block diagram of the margin of eastern North America (~400-350 Mya) showing the effects of the Acadian Orogeny. The Acadian Orogeny added the rocks of the Nashoba Volcanic Arc and Avalonia to North America.

The subduction zone was long lived and consumed a great distance of southeastern Iapetos Ocean crust before finally reaching Laurentia. As a result, the accretionary wedge that accumulated above the subduction zone was very thick and included ocean-floor sediments ranging in age from Early Ordovician (490-470 Mya) to Early Devonian (~420-390). A large region of eastern Connecticut's gneiss and schist bedrock was part of the Acadian accretionary wedge (Figure 17C). These rocks are collectively referred to on the Bedrock Geological Map of Connecticut (Rodgers, 1985), as the "Merrimack Synclinorium" and include the Ordovician (490-443 Mya) Brimfield Schist, the Tatnic Hill Formation, and the Silurian (440-417 Mya) and Devonian (417-354 Mya) Hebron Gneiss and Scotland Schist.

The Nashoba Volcanic Arc, which also formed above the subduction zone along the northern edge of Avalonia, forms a wide belt of rocks in eastern Connecticut (Figure 17C) and includes Ordovician granitic and mafic rocks of the Quinebaug Formation and the Preston Gabbro. Avalonian continental crust lies along the eastern border of Connecticut and in the southeastern corner of the state (Figure 17C). Avalonian bedrock consists mostly of granitic gneiss with minor amounts of dark to medium gray gneiss. Formations include the Branford Gneiss, the Light House Gneiss, the Stony Creek Granite Gneiss, the Hope Valley Alaskite Gneiss, the Ponaganset Gneiss, the Plainfield Formation (quartzite), the Potter Hill Granite Gneiss, the Waterford Group, the Mamacoke Formation, the New London Gneiss, and the Rope Ferry Gneiss.

During the collision of Avalonia with Laurentia, most of Connecticut was compressed. Rocks were crunched and squeezed and large areas were buried 10-20 miles beneath the earth's surface. Layers of rock that were originally flat-lying, were folded into large folds and broken along faults that displaced slices of crust many miles. All of the bedrock now exposed, west of the Avalon terrane and east of Cameron's line (Figure 18), (except for the younger Newark Terrane rocks) was metamorphosed by the heat and pressure from being buried and squeezed during the Acadian Orogeny. Rocks that were originally marine sediments at the Laurentian continental margin and on the floor of the Iapetos Ocean were metamorphosed into schists and gneisses. Some areas were buried deeply enough to partially melt and produce **intrusive** igneous rocks. Rocks that originated as Devonian igneous intrusions in eastern Connecticut include the Canterbury Gneiss, the Lebanon Gabbro, and the Maromas Granite Gneiss (Figure 17C). Devonian granites also intruded western Connecticut and include the Nonewaug Granite.

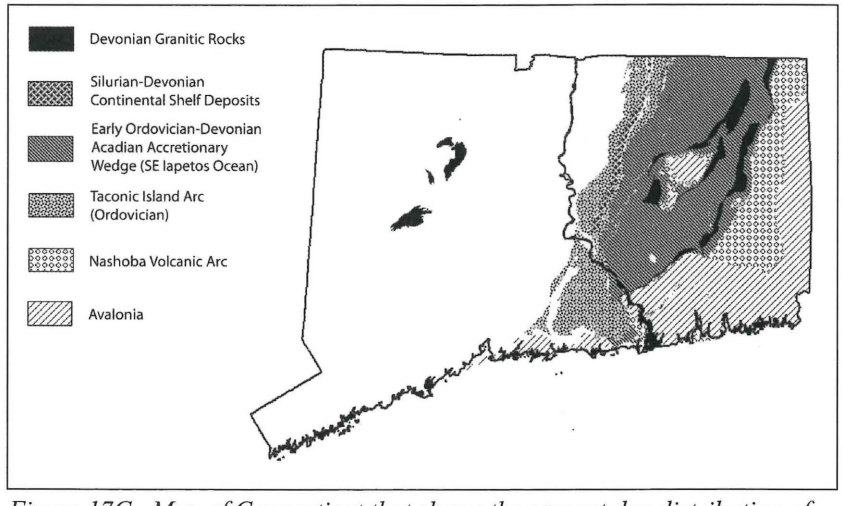


Figure 17C. Map of Connecticut that shows the present day distribution of rocks from Avalonia, Nashoba Volcanic Arc, Taconic Island Arc, Acadian Accretionary Wedge, Silurian-Devonian Continental Shelf and Devonian Granites.

Generalized Bedrock Geologic Map of Connecticut

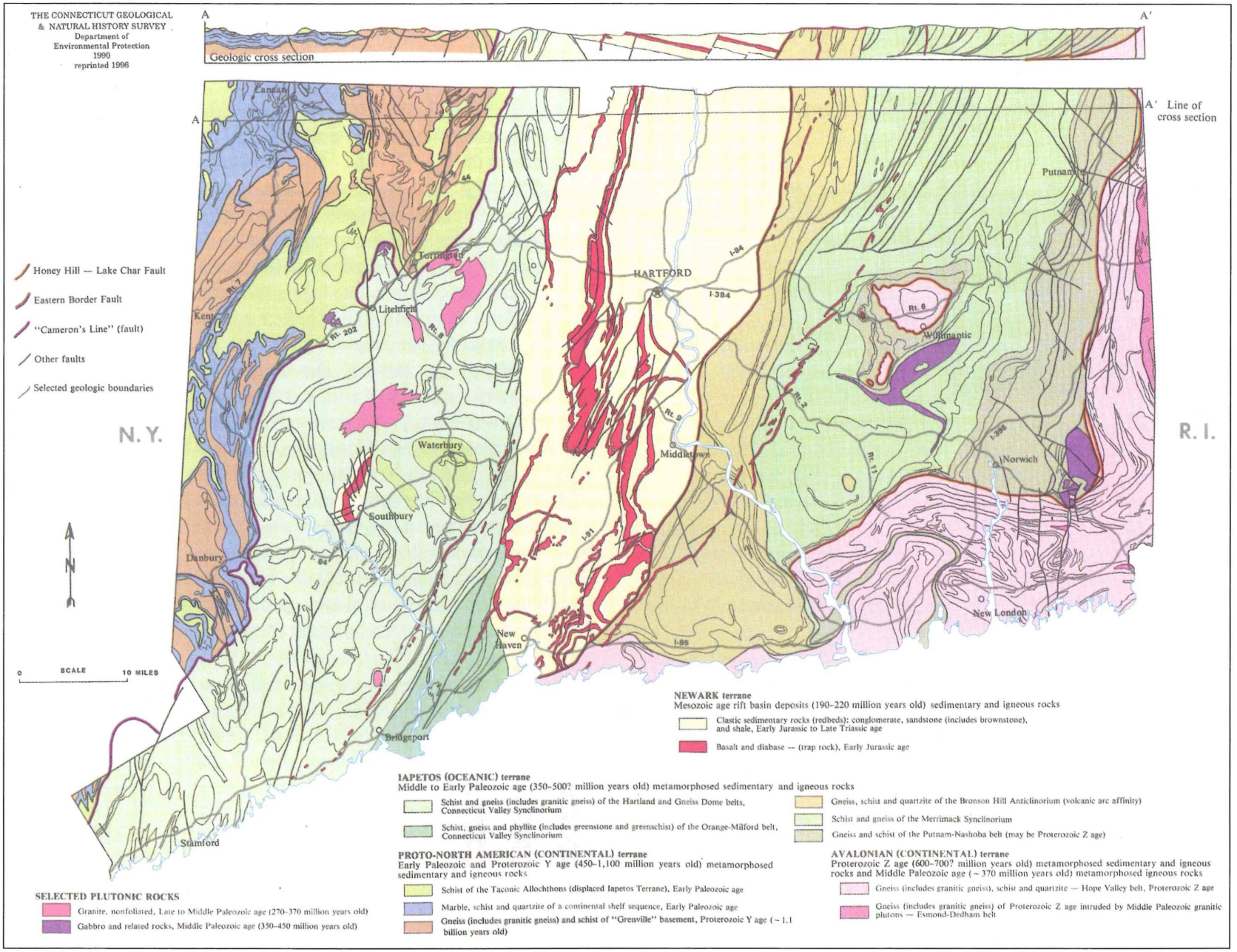


Figure 18. Generalized bedrock geologic map of Connecticut (Rodgers, 1996).

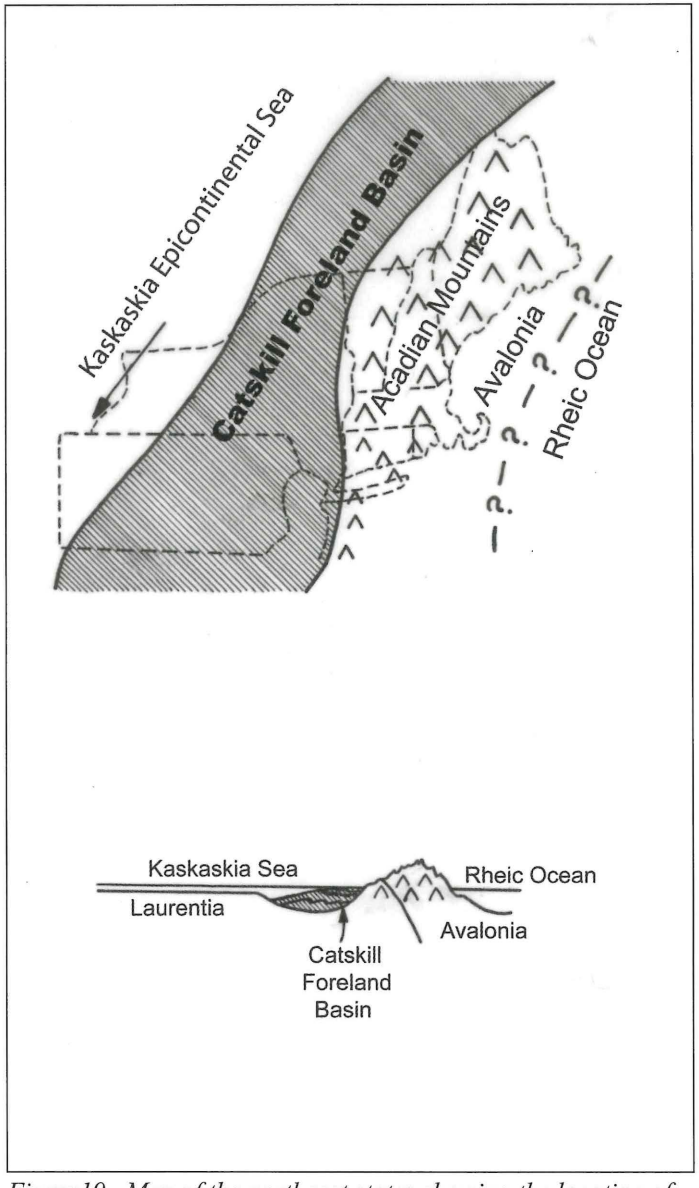


Figure19. Map of the northeast states showing the location of the Acadian Mountains, Catskill Foreland Basin and Kaskaskia Epicontinental Sea at 350 Mya.

It remains ambiguous how much of the metamorphism and deformation in the rocks of Connecticut was caused by the Acadian Orogeny. The reason why it is difficult to determine the effects of the Acadian Orogeny is because it was followed, 40 million years later, by the collision of the much larger continent, Gondwana, with Laurentia. Sorting out the effects of the Acadian Orogeny on the bedrock of Connecticut is like trying to assess damage done to a house hit by a compact car, just before a freight train plowed into the house, with the car caught in between.

By 350 million years ago, the Acadian Orogeny was over. Most of Connecticut was part of a long continuous mountain chain that extended from southern Virginia to Newfoundland. To the west of the Connecticut Acadian Mountains there was a deep narrow inland ocean basin, called the Catskill Foreland Basin (Figure 19). It widened towards the south into the Kaskaskia Epicontinental Sea which covered most of North America. To the east of the Acadian Mountains was the Rheic Ocean that separated North America from Gondwana. The Acadian Mountains quietly eroded over the next 40 million years before an even larger mountain building event, the Alleghenian Orogeny, would again transform the landscape and geology.

Continental collision and the formation of Pangea (310-270 Mya)

In the Late Carboniferous (~320-290 Mya) (Figure 20) part of Gondwana (northwest Africa) collided with the eastern seaboard of Old Red (North America), resulting in the last major orogenic event to affect eastern North America, the Alleghenian Orogeny (Figure 21A). At roughly the same time as the Alleghenian Orogeny was happening, another part of Gondwana (South America) merged with the Gulf coast of North America and formed the Ouachita Mountains. Northern Gondwana also collided with southern Europe (Baltica) to form the Hercynian Mountains. Proto-North America, South America, and Africa were sutured together as part of the supercontinent Pangea. Pangea stretched from the North Pole to the South Pole and separated the Panthalassic Ocean on the west from the Paleo-Tethys Ocean to the east (Figure 21A). Reptiles roamed the large continent during the Permian (290-250 Mya), and a major extinction event ended at least 75% of life on the planet by the end of the Paleozoic. Ultimately Pangea would rift apart during the Jurassic (206-144 Mya) and give birth to the present day Atlantic Ocean.

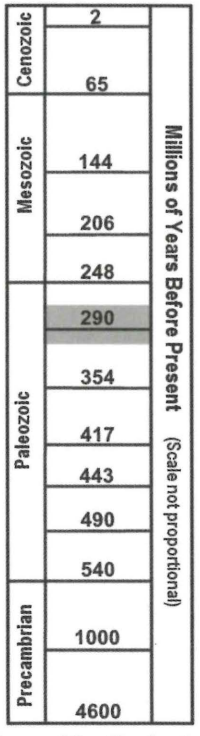


Figure 20. Geologic time scale with time frame highlighted for continental collision leading to formation of the supercontinent Pangea.

The Alleghenian Orogeny was a continental collision and produced a mountain chain, the Appalachian Mountains, along the east coast similar in size to the Himalayas. All of Connecticut was profoundly affected and most of the deformation and metamorphism we see today in the road cuts and outcrops throughout the state are a direct result of Gondwana plowing into Laurentia. Before Gondwana hit, Connecticut was much wider from east to west, perhaps twice as wide, as it is now. After the Alleghenian Orogeny was over, it was as if a giant bulldozer had slammed into the east coast, and compressed the continental crust, scooping up and overturning large chunks of crust. The continental crust beneath Connecticut was probably twice as thick (~50 miles thick) by the end of the collision. In fact the mountains were built up to such a towering height, that giant slow moving landslides, called normal faults, were triggered by the weight of the mountains. What we see now are only the roots of these once gigantic mountains. The Alleghenian Orogeny culminated between 310-270 Mya, and was probably mostly eroded away by about 240 Mya.

The history of the Alleghenian Orogeny in Connecticut is difficult to unravel because any sedimentary or volcanic rock that was deposited at that time has been eroded away and the Rheic Ocean crust completely subducted. The only evidence of the Alleghenian Orogeny is the intense deformation and metamorphism it imposed on the rocks that were already there (Figure 21B).

An amazing result of Africa colliding with North America is that it managed to shove most of Avalon underneath the eastern half of Connecticut (Figure 22A & B). When continents continue to collide, after all the intervening oceanic crust is subducted, intense folding and faulting of the colliding continental crust takes place because the buoyancy of the continental crust keeps it from subducting. However, if the crust of one continent is much older, it is usually colder, denser, and more rigid, so it may be partially subducted, or wedged beneath the younger continental crust. The Avalonian crust that was previously added to Laurentia, was much older (Precambrian) and more rigid than the Silurian-Devonian margin of Laurentia. As a result, Avalonia was shoved underneath eastern Laurentia, as Gondwana continued to impinge on it (Figure 22B). Avalonia is now the "lower plate" to most of the eastern half of Connecticut. If you were to drill holes several miles deep through the Paleozoic rocks of eastern Connecticut, you would eventually hit Precambrian Avalonian bedrock.

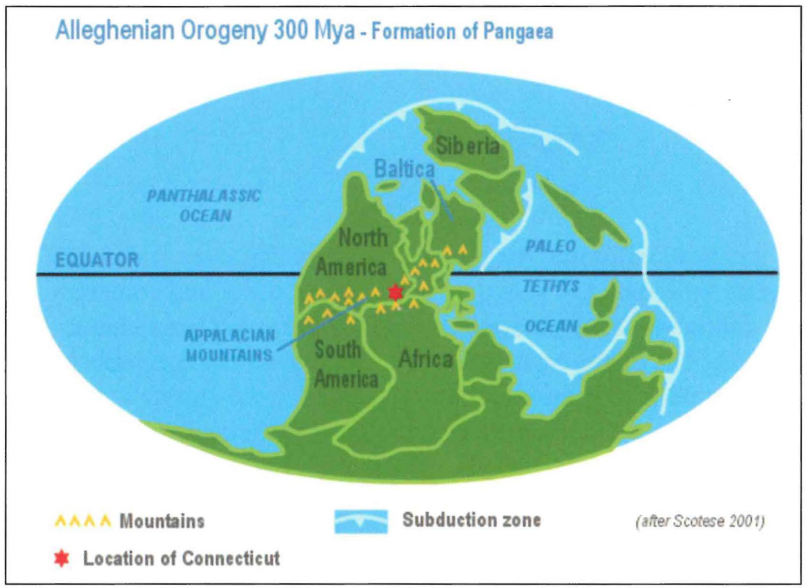


Figure 21A. Reconstruction of the position of the continents 300 Mya during the Alleghenian Orogeny (after Scotese 2001).

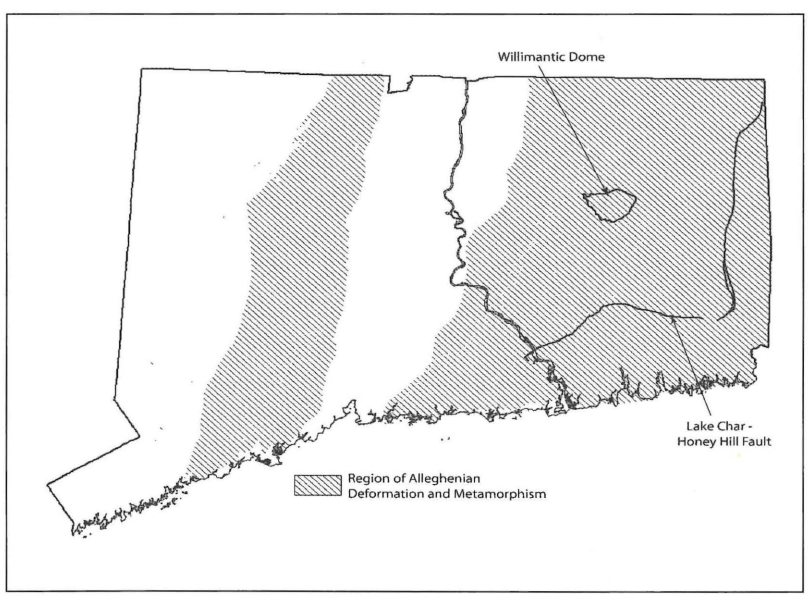


Figure 21B. Map of Connecticut shows the region affected by the Alleghenian Orogeny. Rocks in the Hartford Basin also affected, but are now covered by Mesozoic rocks.

Some of the only Pennsylvanian-Permain age rocks (310-270 Mya) in Connecticut are true granitic rocks within Avalonian crust, such as the Narragansett Pier Granite, that formed by partial melting of Avalonia when it was buried beneath the eastern margin of Laurentia. There are also numerous Pennsylvanian-Permian age pegmatite **sills** and **dikes** that intrude the upper plate Paleozoic rocks and are probably also derived from fluids that migrated up through the upper plate from the partial melting of the Avalonian plate below.

While the Appalachian Mountains were being built up during the plate collision, they were also being torn down by normal faults (Figure 22C). A large normal fault, the Lake Char-Honey Hill fault, is the boundary between Avalonian crust and the Paleozoic upper plate rocks. The Lake Char-Honey Hill Fault (Figure 18) was active as a normal fault from about 290 to 270 million years ago and may have been the original fault surface along which Avalonia was shoved underneath Laurentia. Normal faults are commonly found within continental collision zones and have been documented in most mountain belts formed by plate collisions, such as the Himalayas, the Alps, and the Rocky Mountains. The trace of the Lake Char-Honey Hill fault is also exposed in the middle of the Merrimack terrane in a dome-shape exposure of Avalonia called the Willimantic Dome (Figure 21B). **Isostatic** adjustments of the lower plate rocks after normal faulting and erosion of the overlying Paleozoic rocks uncovered this "tectonic window" of the lower plate (Figure 22D).

The extent of Alleghenian deformation, metamorphism, and partial melting within Connecticut rocks is still being studied and is not yet completely understood. Despite the uncertain details, we know that by ~270 Mya, Connecticut was part of a huge mountain chain that marked the suture between North America and Africa, which were then all part of the supercontinent Pangea.

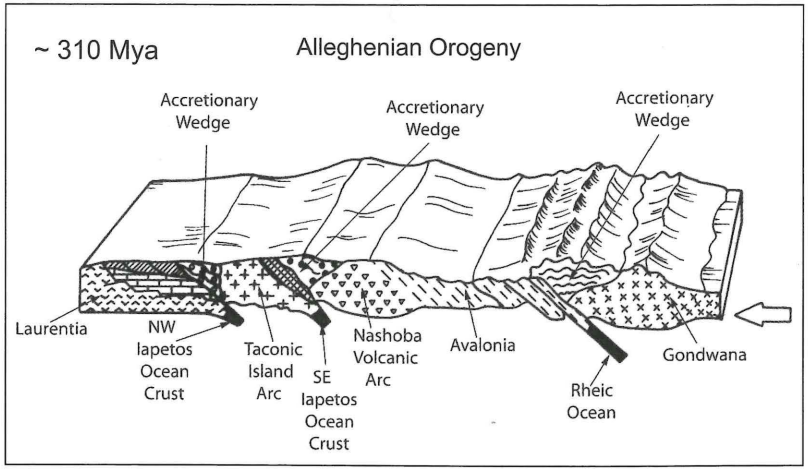


Figure 22A. Block diagram of the Connecticut region (~310 Mya), during the beginning of the continental collision that formed Pangea.

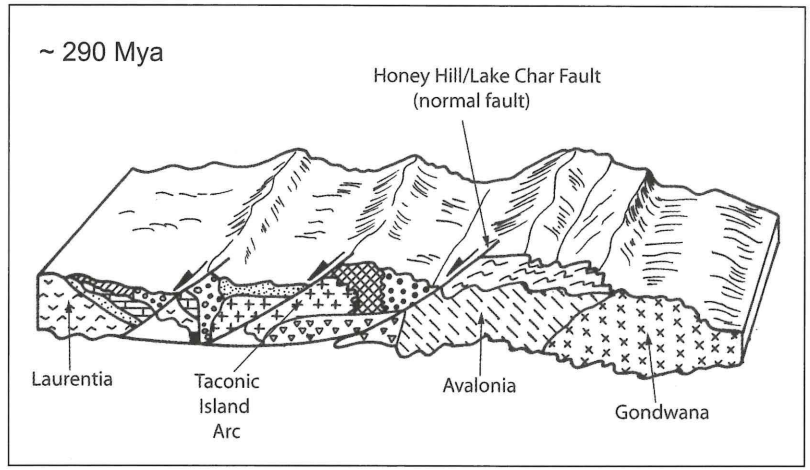


Figure 22C. Block diagram of Appalachian Mountains in Connecticut (~290 Mya). Normal faults that act like giant landslides are adjacent to black arrows which indicate relative movement of either side of the faults.

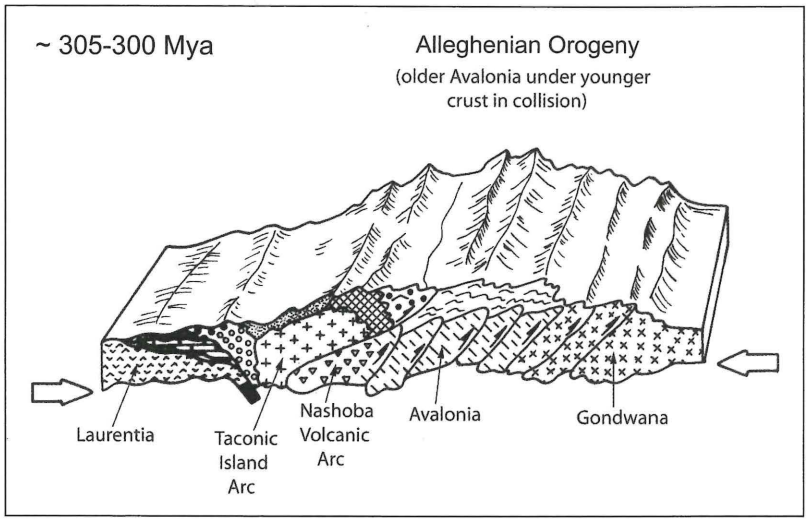


Figure 22B. Block diagram of the Connecticut region (~305 to 300 Mya), showing large mountain range and thickening of the continental crust from continued collision of Gondwana with North America (Laurentia).

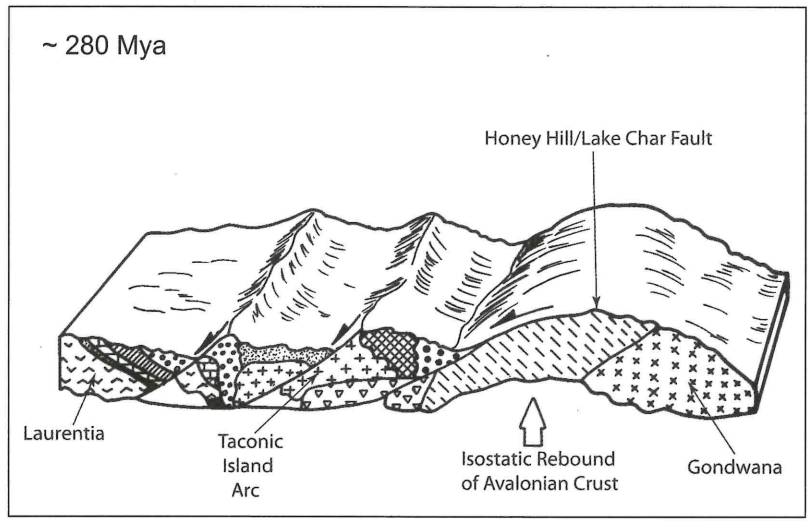


Figure 22D. Block diagram of the Connecticut region ~280 Mya showing the dome shape of the Avalonian rocks in response to isostatic adjustments after normal faulting.

Rifting of Pangea and the birth of the Atlantic (225-180 Mya)

Similar to the billion-year-old supercontinent Rodinia, Pangea did not remain intact for too long in geologic terms. During the Triassic and Jurassic periods (220-180 Mya) (Figure 23) North America and Africa started to pull apart (Figure 24A) and a divergent plate boundary started to form right up the middle of Connecticut (Figure 24B). A wide rift valley formed from the southern part of Connecticut (and probably further south) to northern Massachusetts, and was flanked by steep fault scarps and mountains to the east and west. As rifting progressed, basaltic lava flows flooded the valley floor and sediments eroded off of the highlands and gradually filled in the valley. For some unknown reason, rifting ceased in the Hartford Rift Basin in the early Jurassic and continued along a rift farther to the east that opened the Atlantic Ocean. The Triassic and Jurassic rocks of the Connecticut River valley clearly record the events of that time.

The Mesozoic sedimentary rocks that were deposited and the basalts that were extruded into the rift valley collectively form the Hartford Rift Basin (Figure 24B). The Hartford Rift Basin rocks are the only part of Connecticut that was not involved in a plate collision. As a result, these rocks retain their primary sedimentary and igneous features and are much easier to interpret than Connecticut's older rocks. The sedimentary rocks within the valley contain a wealth of information about the structure of the original rift valley, the climate at the time of deposition and the life that existed then. The sedimentary rocks are **clastic**, and fragments of schists and gneiss, derived from the Paleozoic rocks to the east and west can be found in them. The type of weathering that produced the richly colored brownstones and redbeds alternating with dark shales, which crop out throughout the valley, indicate a tropical climate with alternating dry and monsoon seasons. Forests thrived and the tracks of three-toed dinosaurs are preserved within ancient mud flats. A vastly different world than we see today has been pieced together by the geologic clues preserved within the rocks of the Hartford Basin.

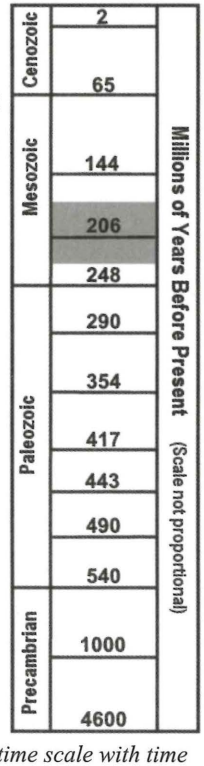


Figure 23. Geologic time scale with time frame highlighted for break up of Pangea.

In structural geologic terms the Hartford Rift Basin is a **graben**. Rift valleys that are flanked by two normal faults are called grabens. If one of the faults has had more displacement across it than the other, the rift valley becomes asymmetric (one side is deeper than the other) and it is called a half-graben. The Hartford Basin is a half-graben and the main fault, the Eastern Border Fault, follows the eastern edge of the rift (Figure 24B & C). The Eastern Border Fault was active throughout the formation of the basin. Continued movement across the fault after the basin filled, caused the sedimentary and basaltic layers within the basin to tilt towards the east. The resistant basaltic flows and **diabase** layers lie between less resistant sedimentary layers and form the prominent ridges known as "trap rock" ridges. These include East Rock and West Rock in the New Haven area, Sleeping Giant in Hamden, Mount Higby in Middlefield, and Talcott Mountain northwest of Hartford (for a more detailed geologic history of the Hartford Basin see McHone (2004)).

Although the Hartford Rift Basin is the most prominent Mesozoic structure, the rest of Connecticut is also laced with Mesozoic faults and fractures that formed in response to tensional forces during rifting. The extensional faults shown on Figure 24B are the traces of prominent brittle faults that have been identified throughout Connecticut. One of the better known of these faults is the Lantern Hill Fault in Ledyard. Most Mesozoic faults such as the Lantern Hill Fault had minor displacement compared to the Eastern Border Fault. None-the-less, these faults have had a profound effect on the shape of the Connecticut landscape. Many of the prominent

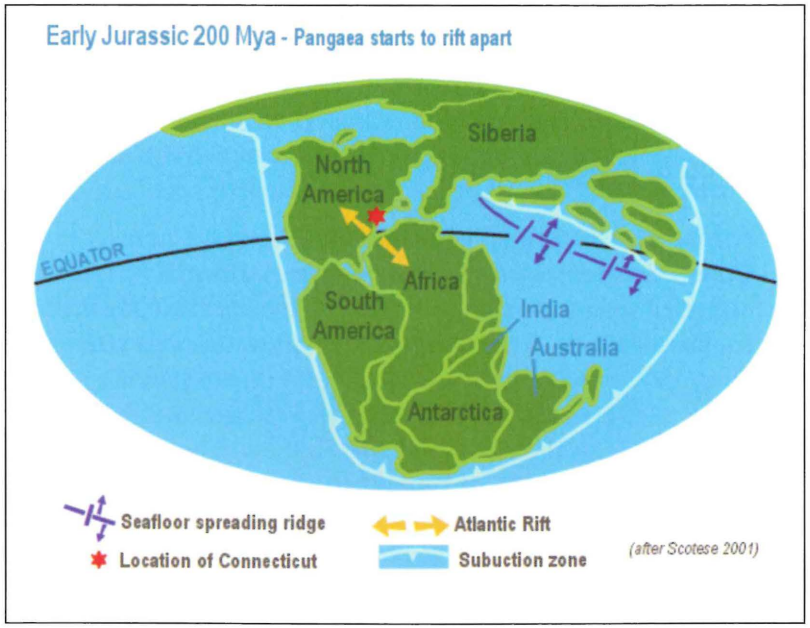


Figure 24A. Reconstruction of the continents 200 Mya (after Scotese, 2001).

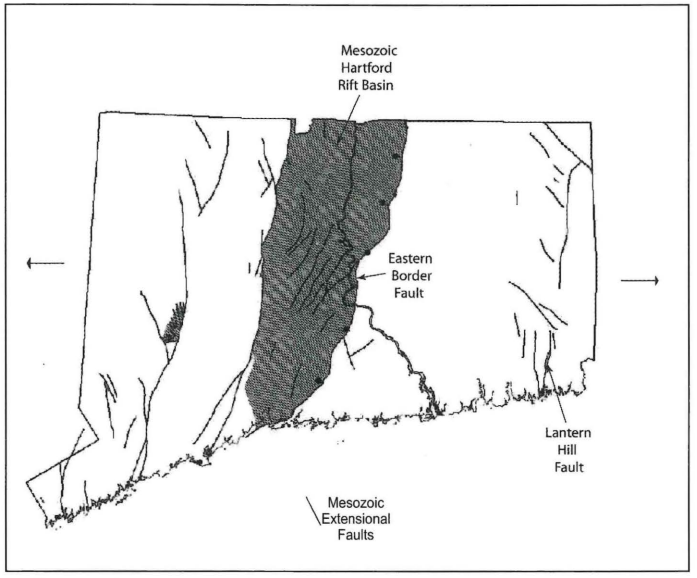


Figure 24B. Map of Connecticut that shows the distribution of Mesozoic sedimentary and igneous rocks deposited in the Hartford Rift Basin. Mesozoic extensional faults are also shown.

valleys and rivers of Connecticut follow north-south trending linear features that are directly related to Mesozoic faults and fractures. Faults and fractures can be conduits for water and the locus of preferential weathering, and thus, often control the path that rivers and glaciers follow. Planes of weakness within rock are controlled not only by faults and fractures, but also by the tectonic and metamorphic layering (called **foliation**) that is common throughout most of Connecticut's bedrock. The trends of most hills and valleys in Connecticut can be attributed to preferential weathering, river and/or glacial erosion concentrated along north-south trending faults, fractures and foliation planes within the bedrock.

Connecticut and eastern North America have remained tectonically quiet for the past 145 million years. Once the Atlantic started to open, the lava flows of the Hartford Basin ceased to spill lava and Connecticut was no longer the locus of colliding and rifting continents. By 145 million years ago Connecticut was part of North America's stable and passive continental crust. Although no longer located at an active tectonic plate boundary, Connecticut continued to move (and continues to move today) as part of the North American plate. The Atlantic Ocean continues to grow as the mid-Atlantic ridge continues to form new ocean crust and push the fragments of Pangea further and further apart. As this happens, the Pacific Ocean is getting smaller through subduction.

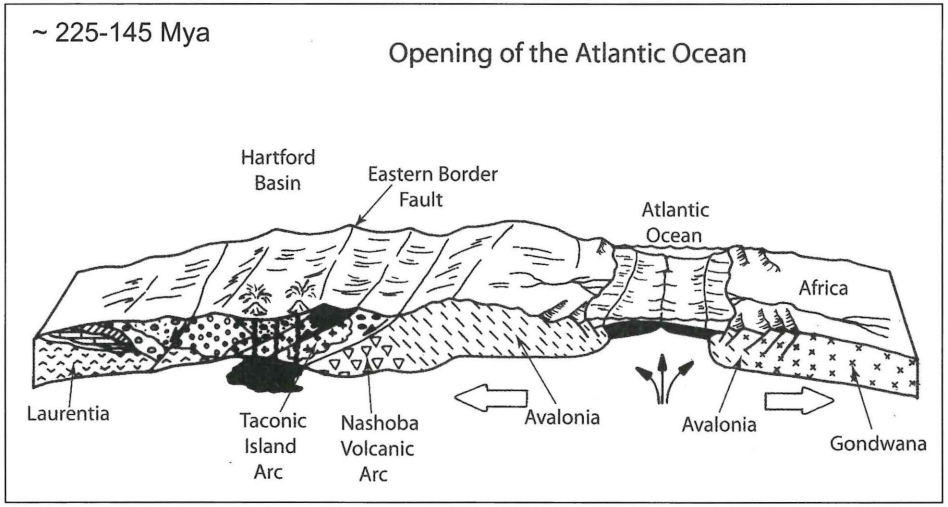
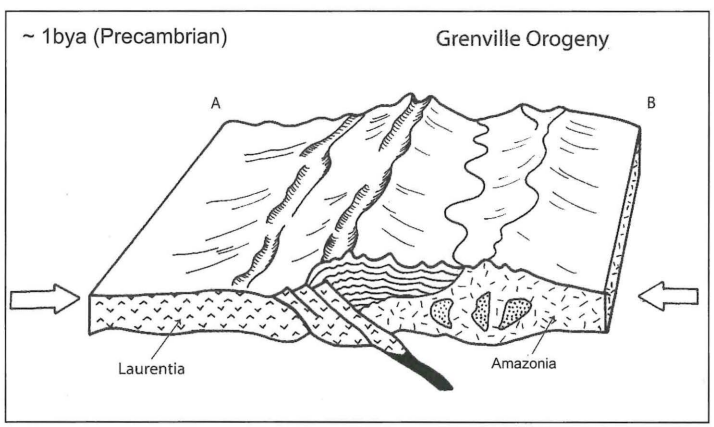


Figure 24C. Block diagram of the Connecticut region 225-145 Mya. The location of the Hartford Rift Basin is shown with active volcanism. The Atlantic Ocean is shown during its early stages.

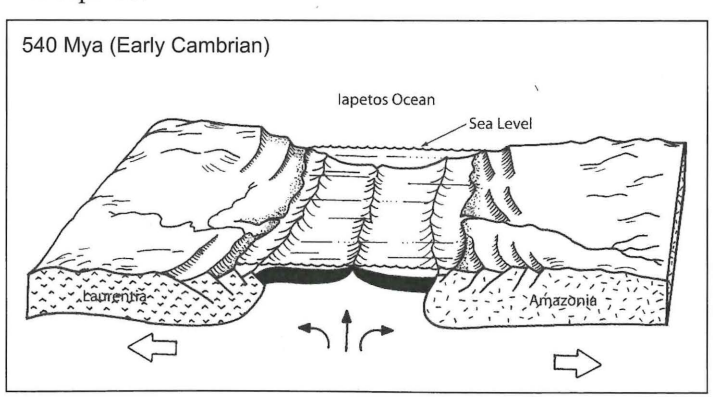
Summary

The geologic history of Connecticut's bedrock is summarized in eight stages (Figure 25 A-H).

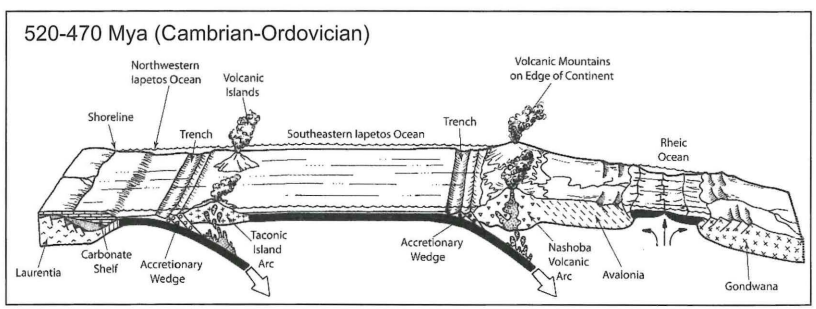
A) It begins with the billion-year-old Grenville Orogeny, during which the Precambrian basement rocks of western Connecticut were metamorphosed and deformed by the collision of Laurentia with Amazonia. The Precambrian rocks of western Connecticut were then part of a Himalayan-sized mountain range called the Grenville that extended from Labrador to Mexico. It was one of the sutures that glued the supercontinent Rodinia together.



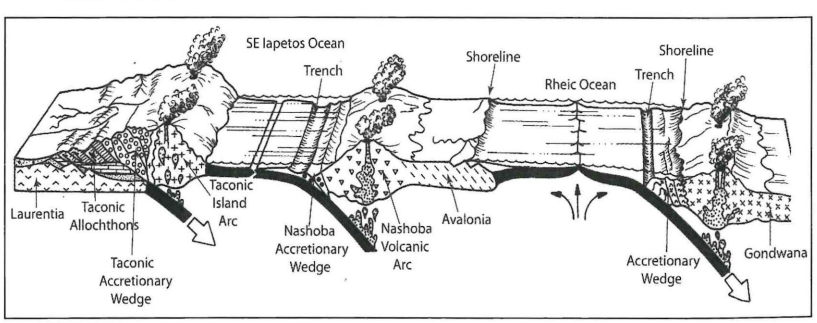
B) Roughly 500 million years after the Grenville Orogeny, Rodinia rifted apart along the trace of the eroded Grenville Orogeny, and left western Connecticut at the edge of a growing ocean, the Iapetos.



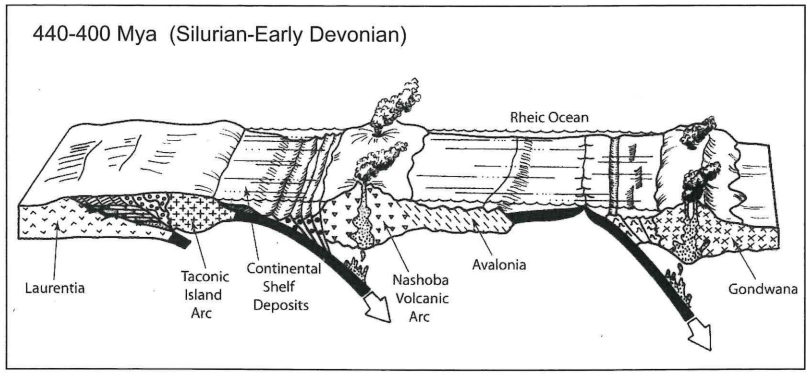
C) For the next 70 million years (520-470 Mya) western Connecticut remained part of a passive continental margin and collected sediments along a broad continental shelf at a warm southern latitude as the Iapetos Ocean grew to a vast size. Towards the end of this time the Iapetos Ocean started to close. In the middle of the Iapetos, ocean floor started to subduct and formed the Taconic Island Arc. In the southeastern Iapetos Ocean a thin fragment of Gondwana, Avalonia, rifted away and drifted toward the northwest over another southeast-dipping subduction zone.



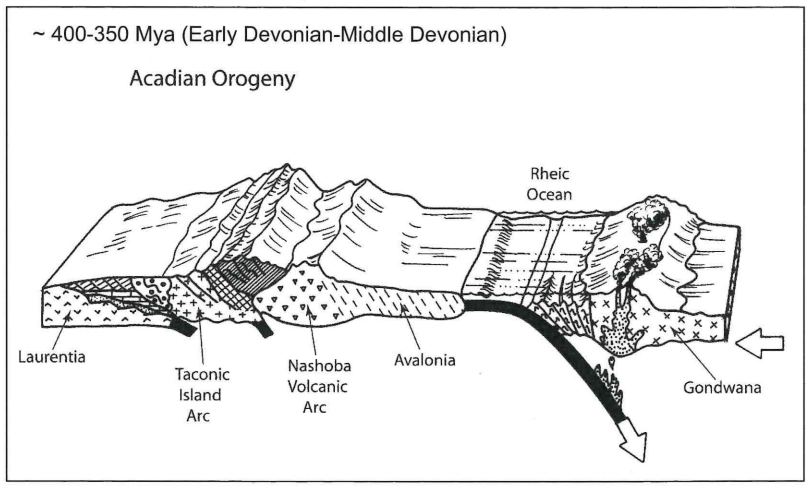
D) By about 440 Mya all of the Iapetos Ocean floor between the Taconic Island Arc and Laurentia subducted, and the Taconic Island Arc collided with Laurentia culminating in a mountain-building event called the Taconic Orogeny. During this time, the remaining southeastern Iapetos Ocean continued to subduct beneath Avalonia, forming the Nashoba Volcanic Arc. Also, a large ocean basin, the Rheic Ocean, existed between Avalonia and Gondwana.



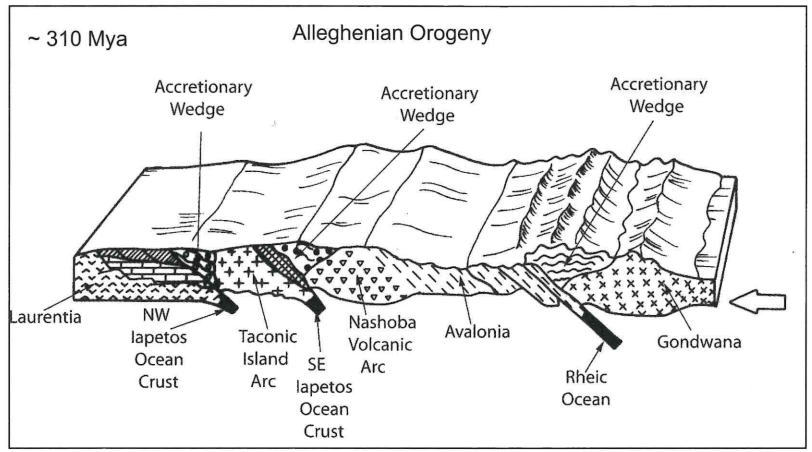
E) After the Taconic Orogeny, from about 440-400 Mya, the Taconic Mountains eroded and the southeastern margin of Laurentia was again part of a passive continental margin and collected sediments along a continental shelf. Meanwhile, the southeastern Iapetos Ocean basin continued to narrrow as its ocean floor subducted beneath the Nashoba Volcanic Arc.



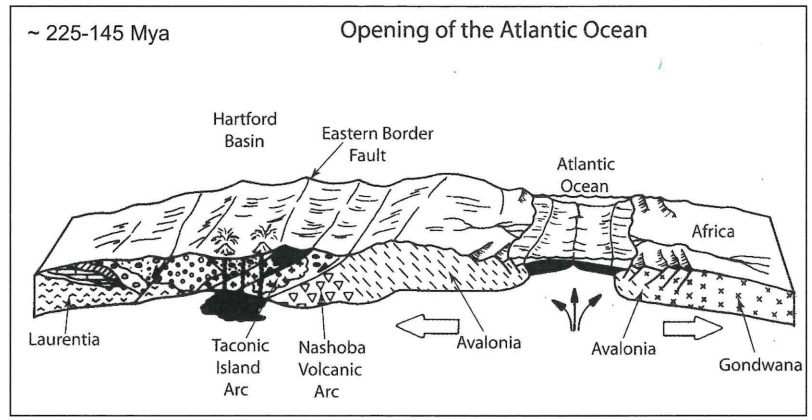
F) Sometime between ~400 and 350 Mya, the last of the southeastern Iapetos ocean floor subducted and Avalonia collided with Laurentia during the Acadian Orogeny. The Rheic Ocean started to close during this time and Gondwana moved towards Laurentia over a southeastern dipping subduction zone.



G) By about 310 Mya the Rheic Ocean closed and Gondwana collided with Laurentia during the final plate collision to affect the east coast of North America, the Alleghenian Orogeny. In that event, Avalonia was shoved underneath the Acadian-modified Laurentian margin and another Himalayan-sized mountain range extended along the east coast of North America. Laurentia and Gondwana were part of the supercontinent Pangaea. Between about 290 and 270 Mya, partly during and after Gondwana was impinging on Laurentia, large normal faults formed in response to the great weight of the thickened continental crust and partly unburied the Avalonian crust.



H) By 225 Mya Pangea started to rift apart from west to east and caused a deep rift valley (the Hartford Basin) to form, which extends from the southern edge of the state to northern Massachusetts.



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Glossary

The following definitions are modified from the Bates and Jackson (1984) Dictionary of Geological Terms (3rd Edition) and from the Glossary of Press and Siever (2001).

Accretionary wedge A thick wedge of deformed sedimentary rock that accumulates above a subducting oceanic plate. The wedge forms by the leading edge of the upper plate scraping the sediment and sedimentary rock off of the top of the sinking plate, similar to a snowplow forming snow banks.

Allochthon A mass of rock that has been moved a long distance from its place of origin, commonly by a tectonic process such as overthrusting, or gravity sliding.

Amphibole A mineral group with the general formula $A_2B_5(Al,Si)_8O_{22}(OH)_2$, where A is mainly Mg, Fe, Ca, or Na, and B is mainly Mg, Fe^{+2}, Al, or Fe^{+3}.

Amphibolite A metamorphic rock consisting primarily of amphibole and plagioclase feldspar.

Basaltic A petrologic name for the lower layer of earth's crust, composed of rocks that are rich in silica and magnesia. It is equivalent to the oceanic crust and the lower portion of the continental crust.

Belt A geographically discrete and distinct succession of major rock units (similar to sequence).

Carbonate A sediment formed of the carbonates of calcium, magnesium, and/or iron, e.g. limestone and dolomite.

Clastic Pertaining to a rock or sediment composed principally of fragments derived from pre-existing rocks or minerals and transported some distance from their places of origin before lithification.

Crust The outermost layer of the earth consisting of relatively light, low-melting-temperature minerals. Continental crust consists largely of granite. Oceanic crust consists mostly of basalt.

Deposition The laying-down of rock-forming material by any natural agent, e.g. the mechanical settling of sediment from suspension in water.

Diabase An intrusive igneous rock consisting essentially of Na-Ca feldspar and pyroxene.

Dike A tabular body of igneous rock that cuts across the structure of adjacent rocks or cuts massive rocks.

Diorite A group of intrusive igneous rocks intermediate in composition between acidic (granite) and basic (basalt).

Dome An uplift or convex upward structure, circular or elliptical in outline, from which the rocks dip gently away in all directions.

Fault A fracture or fracture zone along which there has been movement of the sides relative to one another parallel to the fracture.

Feldspar A group of abundant rock-forming minerals of the general formula, $MAl(Al,Si)_3O_8$, where M can be K, Na, Ca, Ba, Rb, Sr or Fe. Feldspars are the most widespread of any mineral group and constitute 60% of the earth's crust.

Foliation A set of flat or wavy planes in a metamorphic rock, produced by structural deformation

Gneiss A coarse-grained metamorphic rock that shows banding and parallel alignment of minerals.

Graben An elongate relatively depressed crustal unit or block that is bounded by faults on its long sides.

Granite A coarse-grained, intrusive igneous rock composed of quartz, orthoclase feldspar, sodium-rich plagioclase feldspar, and micas.

Greenstone A field term applied to any low-grade metamorphosed Fe and Mg-rich igneous rock (for example, basalt, gabbro, or diabase). The metamorphic mineral chlorite $(Mg, Fe^{+2}, Fe^{+3})_6AlSi_3O_{10}(OH)_8$ accounts for their greenish cast.

Hornblende The commonest mineral of the amphibole group, $(Ca, Na)_{2-3}(Mg,Fe^{+2},Fe^{+3},Al)_5(Al,Si)_8O_{22}(OH)_2$.

Intrusive An igneous rock that forced its way in a molten state into the country rock. Also called an "intrusion".

Isostatic Adjective of isostasy. Isostasy is the mechanism whereby areas of the crust rise or subside until the mass of their topography is buoyantly supported or compensated by the thickness of crust below, which "floats" on the denser mantle.

Lithify To change to stone, or to petrify; especially to consolidate from a loose sediment to a solid rock.

Magma Molton rock material that forms igneous rocks upon cooling. Magma that reaches the surface is lava.

Mantle The main bulk of the solid Earth, between the crust and the core, ranging from depths of about 40 km to 2900 km. It is composed of dense, magnesium and iron rich silicate minerals and divided into concentric layers by phase changes that are caused by the increase in pressure with depth.

Massif A massive topographic and structural feature, especially in an orogenic belt, commonly formed of rocks more rigid than those of its surroundings. These rocks may be protruding bodies of basement rocks, consolidated during earlier orogenies, or younger plutonic bodies.

Orogen A linear region that has been subjected to folding and other deformation in a mountain-building episode.

Orogeny The tectonic process in which large areas are folded, thrust-faulted, metamorphosed, and subjected to intrusions of magna. The cycle ends with uplift and the formation of mountains.

Pegmatite A vein of extremely coarse-grained granite, often containing economic amounts of rare elements.

Plate tectonics The theory and study of the earth's rigid outer plates and their formation, movement, interactions and destruction; the attempt to explain seismicity, volcanism, mountain building, and evidence of paleomagnetism in terms of plate motions.

Quartz Crystalline silica, an important rock-forming mineral, SiO_2.

Schist A metamorphic rock characterized by strong foliation (layering).

Sequence A geographically discrete succession of major rock units.

Shale A fine-grained elastic sedimentary rock, formed by the compaction of clay, silt, or mud.

Sill A tabular igneous intrusion that parallels the planar structure of the surrounding rock.

Subduction The sinking of an oceanic plate beneath an overriding plate; occurs at convergent plate boundaries.

Subduction zone The zone between a sinking oceanic plate and an overriding plate, descending away from a trench and characterized by high seismicity.

Suture A zone of intensely deformed rocks that marks the boundary where two continents collided.

Terrane A fault-bounded group of rocks with a different geological history than the surrounding rocks. The contiguous terranes formed in different locations.

Trench A long, narrow, deep trough in the seafloor; marks the line along which a plate bends down into a subduction zone.

Unconformity A surface that separates two strata. It represents an interval of time in which deposition stopped, erosion removed some sediments and rock, and deposition resumed.

Weathering The physical disintegration and chemical decomposition of rock at or near the Earth's surface.

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